Newest Developments in the German Explosive Safety Quantitative Risk Analysis Software (ESQRA-GE)

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Abstract

The German explosive safety quantitative risk analysis software (ESQRA-GE) has originally been developed to assess ammunition storage scenarios using a transparent step-by-step risk analysis procedure. Starting with the definition of a scenario including different types of ammunition, storage facilities, barriers, buildings, vehicles and locations of persons, physical hazards due to an unexpected detonation of ammunition are calculated. Apart from blast, fragment and debris throw are considered. Based on the physical hazards, damage of persons, vehicles and buildings is evaluated. Including event frequency of an unexpected detonation of ammunition and the exposure of persons to the hazard source, the individual risk of persons is computed.

The increasing number of international operations of the German armed forces leads to new threat scenarios. Especially the field of explosive ordnance disposal (EOD) and the threat generated by improvised explosive devices (IEDs) can be treated using the methodology of the ESQRA-GE. The focus of the paper is the characterization of new types of hazard sources like pipe bombs and different types of ammunition, e.g. originating from the former USSR, by using fragment matrices generated via experimental, analytical-empirical and numerical approaches. While in an ammunition storage scenario position and orientation of e.g. shells are geometrically restricted, IEDs as well as abandoned explosive ordnance may be arbitrarily positioned and even buried in the ground. To assess safety measures, possible fragment shadows behind barricades are calculated. EOD scenarios can be analyzed using damage zones based on a combination of damage analysis of fragment throw and probits describing blast injuries. In summary, the risk analysis software ESQRA-GE responds to requirements posed by the international character of the missions conducted by the German Armed Forces and now includes in addition to the assessment of ammunition storage, EOD and IED scenarios.

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14. ABSTRACT

The German explosive safety quantitative risk analysis software (ESQRA-GE) has originally been developed to assess ammunition storage scenarios using a transparent step-by-step risk analysis procedure. Starting with the definition of a scenario including different types of ammunition, storage facilities, barriers, buildings, vehicles and locations of persons, physical hazards due to an unexpected detonation of ammunition are calculated. Apart from blast, fragment and debris throw are considered. Based on the physical hazards, damage of persons, vehicles and buildings is evaluated. Including event frequency of an unexpected detonation of ammunition and the exposure of persons to the hazard source, the individual risk of persons is computed. The increasing number of international operations of the German armed forces leads to new threat scenarios. Especially the field of explosive ordnance disposal (EOD) and the threat generated by improvised explosive devices (IEDs) can be treated using the methodology of the ESQRA-GE. The focus of the paper is the characterization of new types of hazard sources like pipe bombs and different types of ammunition, e.g. originating from the former USSR, by using fragment matrices generated via experimental, analytical-empirical and numerical approaches. While in an ammunition storage scenario position and orientation of e.g. shells are geometrically restricted, IEDs as well as abandoned explosive ordnance may be arbitrarily positioned and even buried in the ground. To assess safety measures, possible fragment shadows behind barricades are calculated. EOD scenarios can be analyzed using damage zones based on a combination of damage analysis of fragment throw and probits describing blast injuries. In summary, the risk analysis software ESQRA-GE responds to requirements posed by the international character of the missions conducted by the German Armed Forces and now includes in addition to the assessment of ammunition storage, EOD and IED scenarios.

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Brief presenter biography

Frank Radtke started his working career as a research associate at TU Delft after finishing his studies of civil engineering at the University of Hannover with a Dipl.-Ing.. Since 2009 he has been working at the Fraunhofer-Institute for High-Speed-Dynamics, Ernst-Mach-Institute, in the hazard and risk analysis group. His work mainly focuses on ammunition storage safety and counter terrorism.

1 Introduction

Planning of new ammunition storage facilities or the assessment of existing facilities is normally done following international and national regulations [1, 2]. These regulations mainly employ quantity - distance (QD) tables. This approach has been successfully used for many years. But in a number of cases – especially on deployed missions – it is not possible to comply with these rules. For this purpose risk analysis models can be employed. At the Ernst-Mach-Institute we have developed the German explosive safety quantitative risk analysis model (ESQRA-GE) in collaboration with the German Armed Forces (GAF) and the Technical Centres of the German Armed Forces (WTD 52 and WTD 91). This software tool has originally been designed for the assessment of non-standard ammunition storage scenarios. Since the release of the last version of the ESQRA-GE to the German Ministry of Defence (MOD) in 2006/2007 [3], the software has been re-implemented using more efficient computational techniques and including a number of new features.

Furthermore, the ESQRA-GE is currently extended to new applications different from ammunition storage. The German Armed Forces have to deal with an increasing number of international operations. Although ammunition storage is still an important issue, the focus of the development has shifted slightly to the assessment of threats caused by abandoned explosive ordnance (EOD) and improvised explosive devices (IEDs). It is the task of the explosive ordnance disposal forces of the army to disarm these devices. To maximize their survivability there are guidelines which are documented e.g. in the Hdv 183/100 [4] and the civilian BGR 114 [5]. These two documents specify safety distances depending on the net explosive quantity (NEQ) of the ordnance using QD tables. Within these zones all persons have to be evacuated. To guarantee safety the specified distances are chosen comparatively large. But in IED and EOD scenarios on deployed missions it is almost impossible to comply with these "peacetime" guidelines.

For these cases, a tool is needed that allows for a more detailed assessment of a specific situation. It should take into account the influence of protective measures like barricades or the protective influence of local buildings. In this way, such a tool can help to increase survivability of EOD forces as well as safety of non-involved personnel and civilians even if safety distances cannot comply with guidelines. The natural choice is to extend the range of applicability of the already existing ESQRA-GE to EOD and IED applications and create an extended version called ESQRA-GE EOD.

We first shortly review the advances of German explosive safety quantitative risk analysis software (ESQRA-GE). Then we explain the different aspects that need to be taken into account when applying the ESQRA-GE to scenarios containing explosive ordnance or improvised explosive devices. Finally, we show some examples related to the use of the ESQRA-GE EOD in explosive ordnance applications.

2 German Explosive Safety Quantitative Risk Analysis Model (ESQRA-GE)

Risk can be defined as product of event frequency or probability of event, consequence of an event and the fractional exposure of e.g. persons to hazards [6]. This reads

$$R = C\,E\,F \,, \tag{1}$$

where R denotes the individual risk, C denotes the consequences, E is the fractional exposure and F is the event frequency [7]. In short, risk can be defined as the "likelihood of harm" [8].

The process of risk management is shown in Figure 1. When assessing risk, we need to start with the definition of the scenario: what kind of hazard source do we deal with, how many people might be exposed and at which location are buildings or other infrastructure.

Having defined the scenario, we have to analyse which hazards, e.g. blast or fragments, need to be considered.

Based on these hazards we can calculate the consequences, such as the amount of damage inflicted on buildings or the number of injured persons.

In the next step, we need to perform a probability analysis consisting of an estimation of both the event frequency and the fractional exposure of persons to the analyzed threats. Fractional exposure can be computed for multiple locations and also distinguishing different groups of personnel.

With this information the individual risk can be computed as given in Equation (1). By comparing the calculated risk to standard risks as e.g. the risk to be killed in a car accident, we can evaluate the scenario. Either we accept it or we need to reduce the risk by adding protective measures as for example barricades around a hazard source (refer to Figure 1).

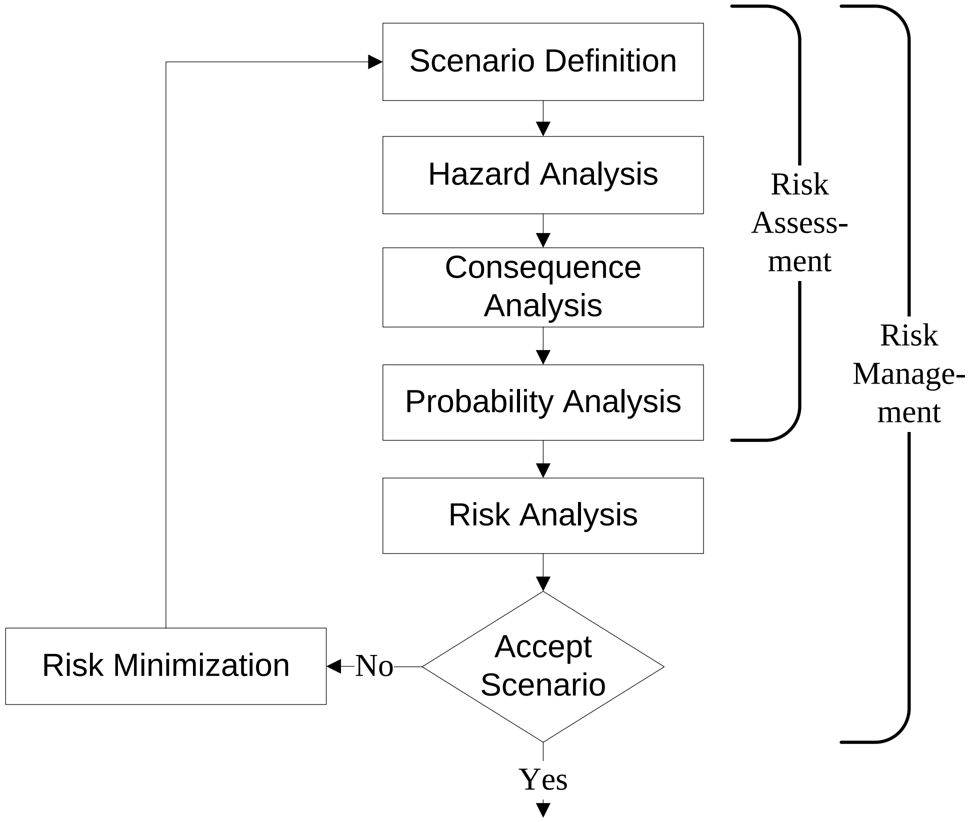

Figure 1: Steps in a typical risk management scheme following [6].

2.1 Scenario Definition

The new version of the German Safety Quantitative Risk Analysis Software features 3D scenario representation on a 2D plane to allow for a faster and more realistic assessment of complicated situations. Geographical information can be included with an underlying map.

By using drag and drop it is easily possible to place potential explosion sites (PES), exposed sites (ES) and barricades according to the outlines on the map. In this way complex scenarios can be quickly generated.

Exposed sites are buildings, un-armoured vehicles, helicopters and persons. An example of a scenario is depicted in Figure 2.

The next step after the scenario definition is the hazard analysis.

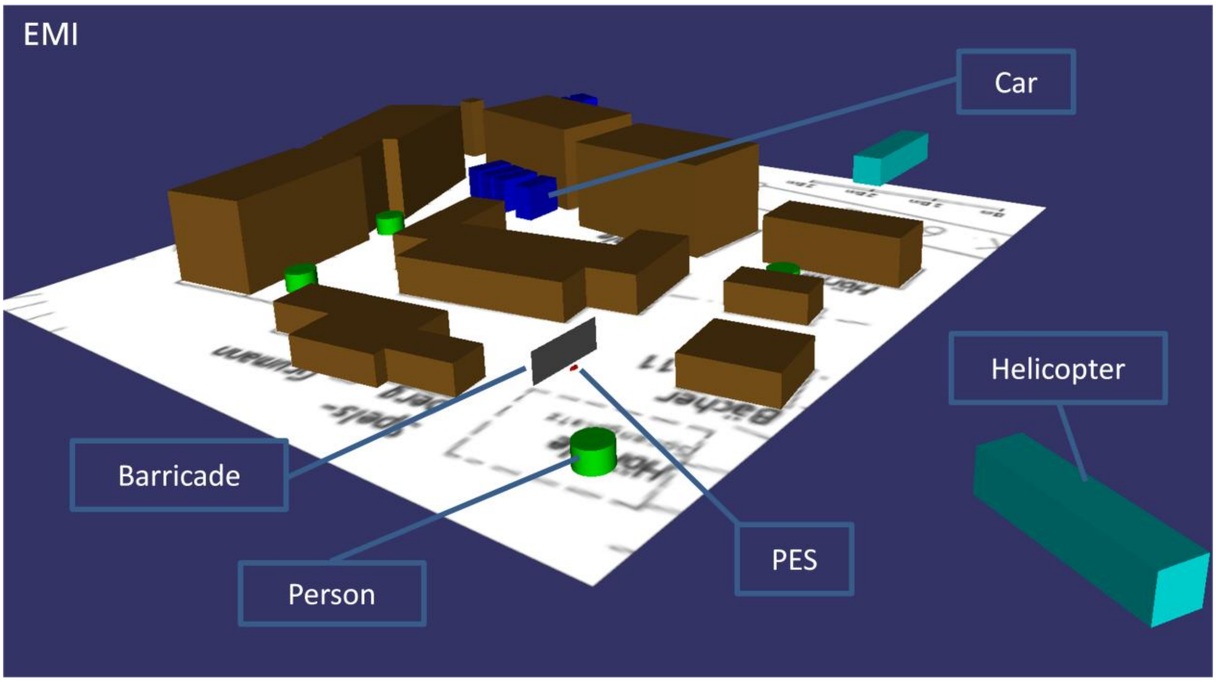

Figure 2: Scenario definition; the Ernst-Mach-Institute at Efringen-Kirchen, Germany.

2.2 Hazard Analysis

Explosive events lead to different hazards such as blast, fragment and debris throw, thermal effects, ground shock and crater ejecta [6]. In the ESQRA-GE, we focus on hazards due to blast and fragments.

Blast effects are calculated based on the net explosive quantity (NEQ) using the simplified Kingery Bulmash polynomials [9] (refer to Figure 3).

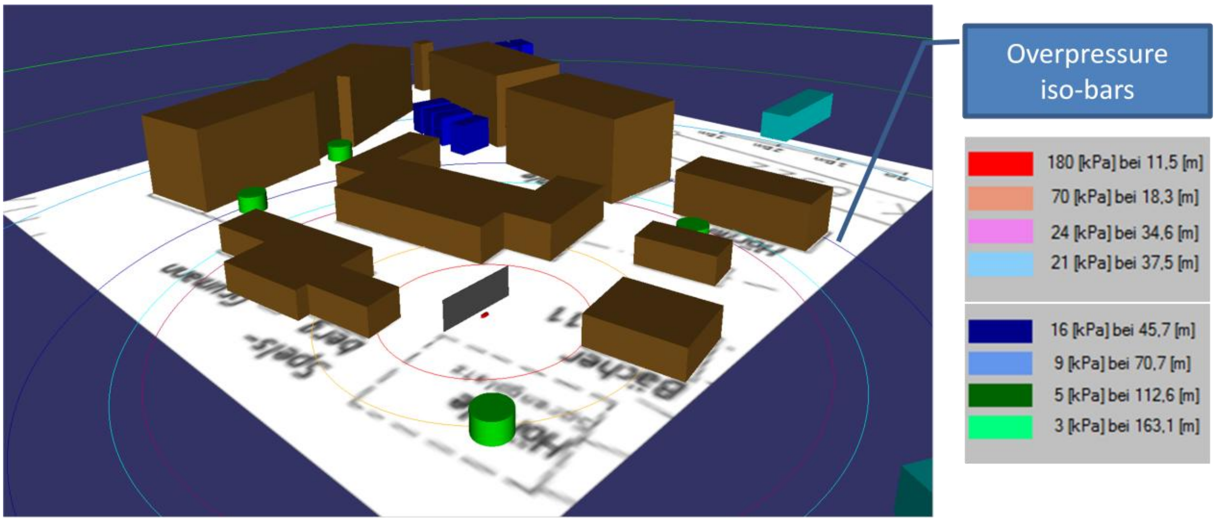

Figure 3: Isobars presenting the side-on blast overpressure.

To describe the fragmentation behaviour of ordnance and the initial launch conditions of individual fragments we employ fragment matrices [10]. A fragment matrix contains information on mass, velocity and angular distribution of fragments originating from a hazard source, as e.g. an artillery shell (refer to Section 3.1).

The fragment trajectories are computed using an intrinsically two dimensional model taking into account gravity and velocity depending drag forces [11, 12].

The hazard source can be placed in any position above or below the surface to simulate e.g. buried abandoned ordnance. Furthermore, it can be arbitrarily oriented.

The common fragment matrix approximates the hazard source as a point source. The fragments are launched using a unit sphere around the point source. This unit sphere is discretized with a regular mesh of three-node elements (only at the poles) and four-node elements (refer to Figure 4).

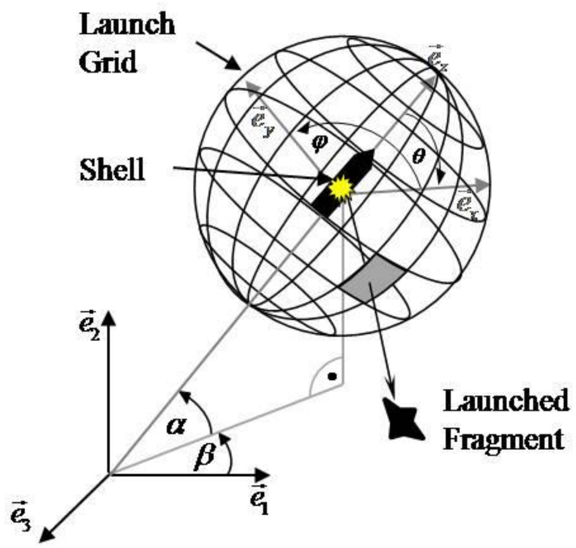

Figure 4: Discretization of the hazard source; through each surface element representative fragments are launched; global and local coordinate systems as well as the corresponding angles are indicated.

From the centre of each element representative fragments are launched with a probability defined as

$$\lambda_{traj} = \frac{A_{elem}}{A_{ring}} , \tag{2}$$

where λ_{traj} is the geometrical probability (trajectory probability) that a fragment passes through a specific surface element of area A_{elem} within the latitude ring of area A_{ring} . Within a typical rotational symmetric fragment matrix for each mass class (mass interval) the number of fragments is given which belongs to a latitude ring. For each latitude ring the average maximum launching velocity of all fragments is given. Using this discretization, the hazard source can be arbitrarily placed and rotated in a simple way.

In the software it is possible to display fragment densities on the ground. For this purpose the ground is discretized with user specified volume elements. The user may set base area and height of the volume elements. Either all fragments or fragments that fulfil the NATO criterion are displayed. According to the NATO criterion the density of

fragments with an energy greater than 79 Joule is shown if the density exceeds one over 56 m². For both densities the fragments are considered that pass through a specified volume element. An example of the fragment density of NATO fragments is shown in Figure 5.

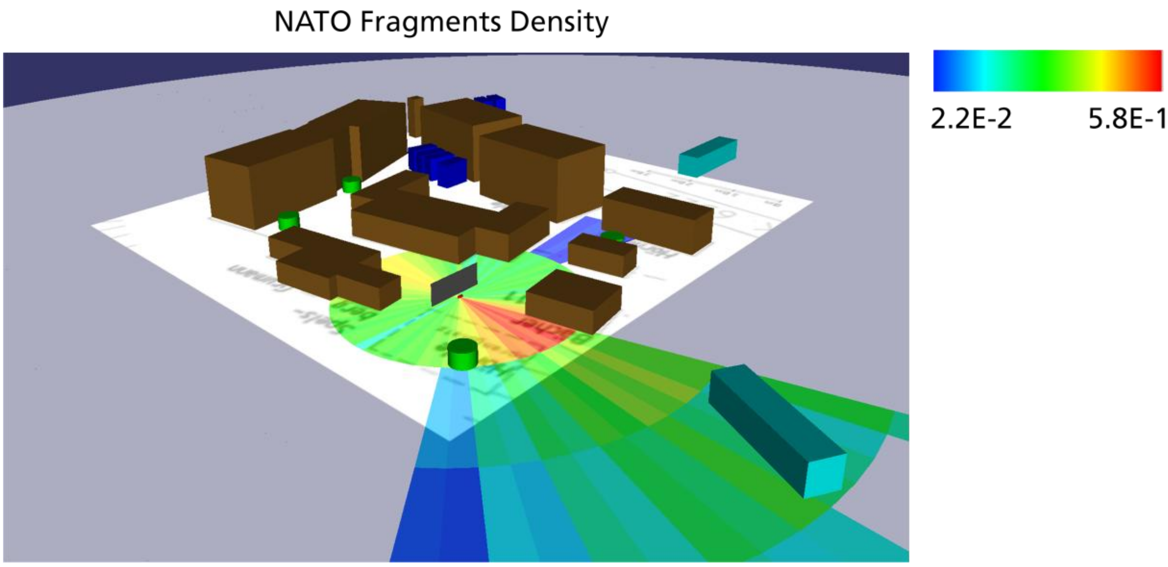

Figure 5: Fragment density according to the NATO criterion.

It is further possible to display the calculated fragment trajectories. In this way fragment shadows behind barricades or buildings are clearly visible. Naturally, the fragment shadow is also depicted in the fragment density plots.

2.3 Consequence Analysis

The consequence analysis considers effects of an explosion on persons, buildings, helicopters and vehicles. The damage is calculated and displayed in the software.

We consider primary, secondary and tertiary blast effects on persons, buildings and vehicles.

Primary blast effects are due to blast overpressure and impulse. We consider lethal lung injuries based on [13] as well as ear injuries using mainly probits [14].

Secondary blast effects are due to fragment throw. We apply the NATO criterion for lethal fragments, i.e. all fragments are considered to be lethal if

$$E_{frag} \geq 79J \,, \tag{3}$$

where E_{frag} describes the kinetic energy of a single fragment.

Furthermore, we use Sellier's skin penetration criterion [15] to describe all possible injuries resulting from fragments: assuming a cube-like shape for a fragment, using the density of the fragment material and taking the fragment energy into account, the energy per area of the fragments can be calculated. A fragment is hazardous if

$$\frac{E_{frag}}{A_{imp}} \geq 10 \frac{J}{cm^2}, \tag{4}$$

where E_{frag} denotes the energy of the fragment and A_{imp} denotes the approximate impact area (presented surface). This information is combined with the probability that a representative fragment hits a person. It consists for each representative fragment that hits a volume element on the ground of interest of a product of the trajectory probability, described in Equation (2) and the geometrical hit probability of a single person situated in the volume. Combining either all lethal or all hazardous representative fragments using Equations (3) or (4), respectively, the individual local risk for lethal or hazardous hits for personnel is computed for the considered volume element.

Tertiary blast effects describe the blow down and displacement of persons due to blast wind. This occurs only for larger NEQs. To describe these effects we employ probits based on [16].

A model considering the combined effect of primary, secondary and tertiary blast effects is used for NEQs larger than 1000kg TNT equivalent. It consist of probits based on information extracted from [1]. For NEQs smaller than 1000 kg TNT equivalent a combination of the effects resulting from fragments and blast is used.

Furthermore, operative damage models for buildings, un-armoured vehicles and helicopters are included that allow for a fast damage assessment

For more detailed information on the damage models implemented in the ESQRA-GE refer to [3].

2.4 Exposure, Event Frequency of Explosive Events and Risk Analysis

In the ESQRA-GE it is possible to specify for individuals or groups of persons the fractional exposure to a certain threat. In this way a profile of the movement of individuals or groups in a field camp can be analysed.

To compute the risk we still need to define the event frequency as given in Equation (1). Regarding ammunition storage scenarios we employ the Probability of Event Matrix developed by the Risk-Based Explosive Criteria Team [3] adapted to German conditions. We include influence factors as the compatibility group of ammunition, the type of activity at the PES and scaling factors for special circumstances.

Finally, the individual risk can be computed as described in Equation (1).

In case of EOD and IED scenarios we are mainly interested in the description of physical hazards and the modelling of consequences. Thus, the probability analysis is excluded from the ESQRA-GE EOD.

3 Application of the ESQRA-GE to Explosive Ordnance Disposal and Improvised Explosive Device Scenarios

As described in Section 1 there is a growing need to assess IED and EOD scenarios on deployed missions of the German Armed Forces in more detail than it is possible using current regulations.

These new scenarios generate different boundary conditions for the ESQRA-GE. Different new types of hazard sources (abandoned ordnance, improvised explosive devices) have to be considered. The abandoned ordnance is mostly not of German or NATO origin, which means, that necessary information to characterize the hazard source is not easily available. Regarding IEDs no detailed information about the employed explosive, the casing or the fuse can be obtained at all.

When assessing EOD or IED scenarios we have to consider smaller amounts of explosives than in ammunition storage scenarios. We have to treat single shells or pipe bombs with net explosive quantities (NEQs) of up to several kilogram compared to several tons in ammunition storage scenarios (excluding large vehicle born improvised explosive devices).

While in an ammunition storage scenario ammunition is stored under rather controlled conditions, in EOD and IED scenarios the hazard source may have every possible position on the ground or might even be partially buried under the surface.

If such a hazard source is detonated in a controlled way by EOD forces the hazard caused by fragments and blast might be different from that if the ordnance is initiated in the way it was designed for. Thus, the classical characterization using arena tests collected in fragment matrix data as described e.g. in [15] might not be applicable.

Furthermore, the analysis of physical hazards and damage due to an explosion of abandoned explosive ordnance or improvised explosive devices has to be adapted to the needs of EOD experts. Regarding the complex situation during an IED or EOD disposal operation the ESQRA-GE is not meant to become a tool used by the soldier in the field but it is supposed to stay an expert tool employed during mission planning.

3.1 Hazard Source Characterization for EOD and IED Scenarios

To be able to calculate the physical hazards caused by abandoned explosive ordnance or improvised explosive devices we need to characterize the hazard sources. Since we consider only blast and fragment hazards, we need information on type and amount of the employed explosives as well as a description of the fragments generated by the hazard source. The latter can be provided in different ways as for example using (combined) angular, mass and velocity distributions for the description of launch conditions, using so called source functions [17] for mass and velocity classes or as fragment matrix [10, 15], which can also be generalized. In the ESQRA-GE we use fragment matrices for rotational symmetric sources as already mentioned in Section 2.2.

They include the number of fragments per mass class and per angle interval. In addition, the maximum launch speed per angle interval is given.

The classical way to obtain fragment matrices are arena tests as described in [15]. But these tests are expensive and time consuming especially when performing extensive studies. Therefore, we have investigated other approaches. We use commercial numerical packages like AutoDyn and SplitX but also analytical approaches as described in [15]. Furthermore, we have performed a number of scaled and full-scale experiments.

In this contribution we present a combination of small scale experiments performed at EMI combined with an analytical approach to generate fragment matrices for small pipe bombs.

Building a fragment matrix requires information on the number of fragments belonging to each combination of mass bin and launch angle interval as well as the maximum velocity for each angle interval:

$$N_{frag} = f(m,\theta) \text{ and } v_{0frag\max} = f(\theta). \tag{5}$$

We use a barrel filled with water to determine the mass distribution. The experimental setup is shown in Figure 6.

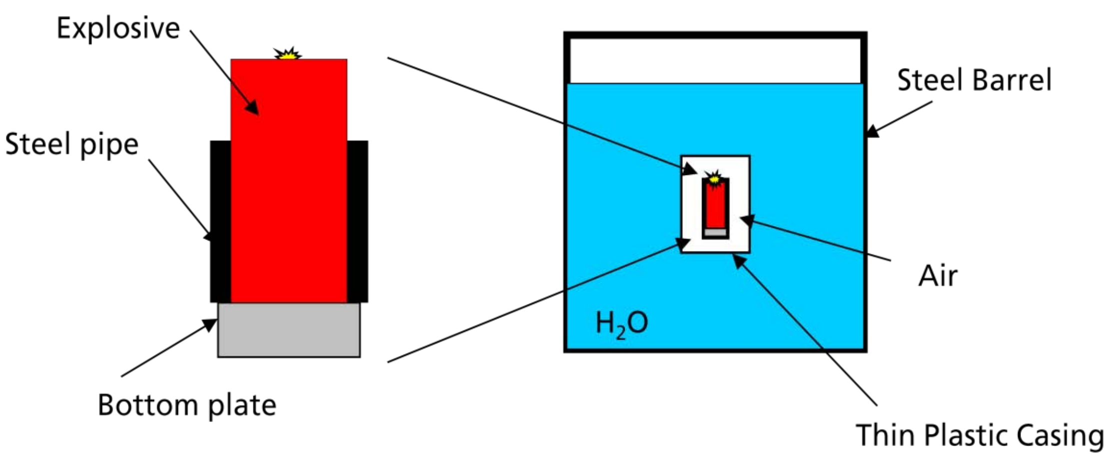

Figure 6: Test setup for small pipe bombs; idealised pipe bomb (left), water filled steel barrel to capture the fragments from a pipe bomb (right).

The pipe bomb is placed in a small plastic cylinder which is filled with air and placed in the water filled barrel. When the pipe bomb explodes, the fragments propagate through the air, pass the plastic cylinder and are finally stopped in the water. The fragments are recovered and the mass distribution can be determined.

The advantage of this method is the relative simplicity of the experiment which makes it possible to perform a larger number of tests with reasonable costs.

Having determined the mass distribution using the water barrel, the fragment velocities and the launch angles are measured using a high speed X-Ray setup as shown schematically in Figure 7.

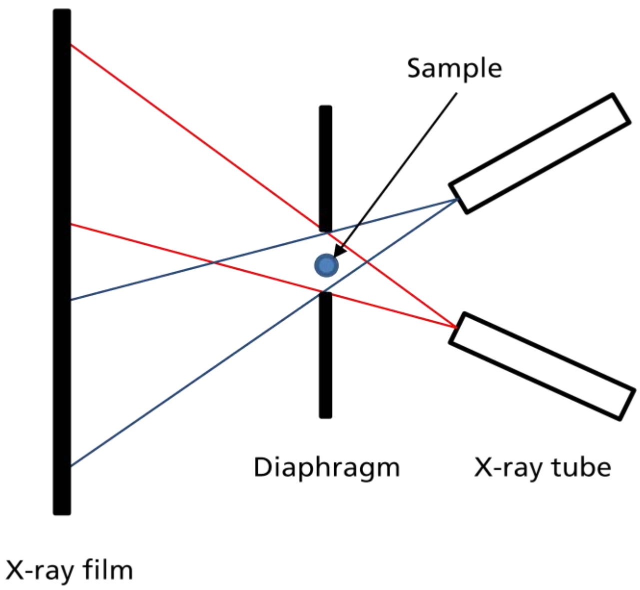

Figure 7: X-ray setup used to study launch velocities and launch angles of fragments.

When the pipe bomb is detonated pictures are taken at two different time steps t_1 and t_2. After correcting the parallactic error the deformation can be extracted and the velocity of the fragment can be calculated. When we test (pipe) bombs with simple geometry and we use two dimensional pictures to investigate this three dimensional problem we can determine only an overall maximum fragment launch speed $v_{0frag\max}$ and the corresponding main launch angle θ_{main}. In combination this yields a fragment matrix containing one row of entries. This is even for rather simple pipe bomb configurations not realistic. As the X-ray photos show (refer to Figure 8) the launch angles of the fragments are somehow smeared over a certain angle interval $\Delta\theta$ around the main launch angle θ_{main}. Therefore, we combine a theoretical smearing approach with the experimental results. This approach is also intendended to capture to a certain extend the unknown variations in the material of the pipe, the geometry and the explosive.

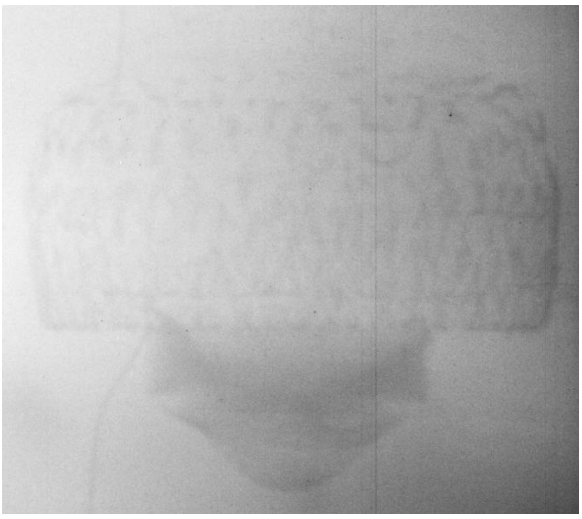

Figure 8: X-ray picture of an exploding pipe bomb; the pipe bomb is completely fragmented, fragments are launched almost horizontally while the bottom plate stays intact and is launched downwards.

As shown in Figure 9 we distribute the number of fragments from the original angle interval θ_i over the adjacent angle intervalls θ_k following a Gaussian normal distribution similar to an approach shown in [15]. The velocities are smeared such that either the original velocitiy of the angle class is kept or, if there is no entry, i.e. no fragments have originally been launched in this interval, an average velocity is used.

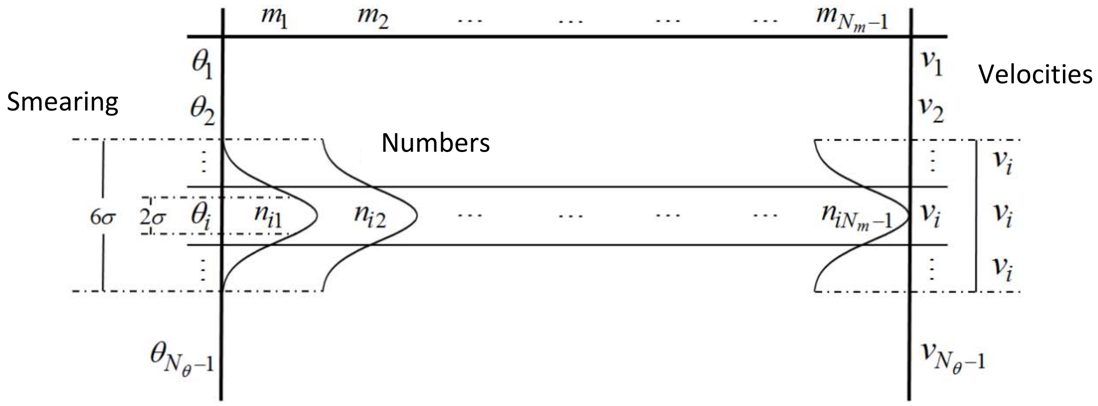

Figure 9: Smearing of a fragment matrix; θ denotes the launch angle class, n denotes the number of fragments of a combination of angel and mass class, v is the average maximum launch velocity of an angle class, m denotes the fragment mass class and σ is the standard deviation of the normal distribution used to smear the fragment matrix.

As an example the fragment density on the ground due to the explosion of a pipe bomb filled with ANFO (length of 60 mm, diameter of 50 mm and shell thickness of 4 mm) is shown in Figure 10. The results from the experimental fragment matrix are compared to the results originating from the analytical smearing approach.

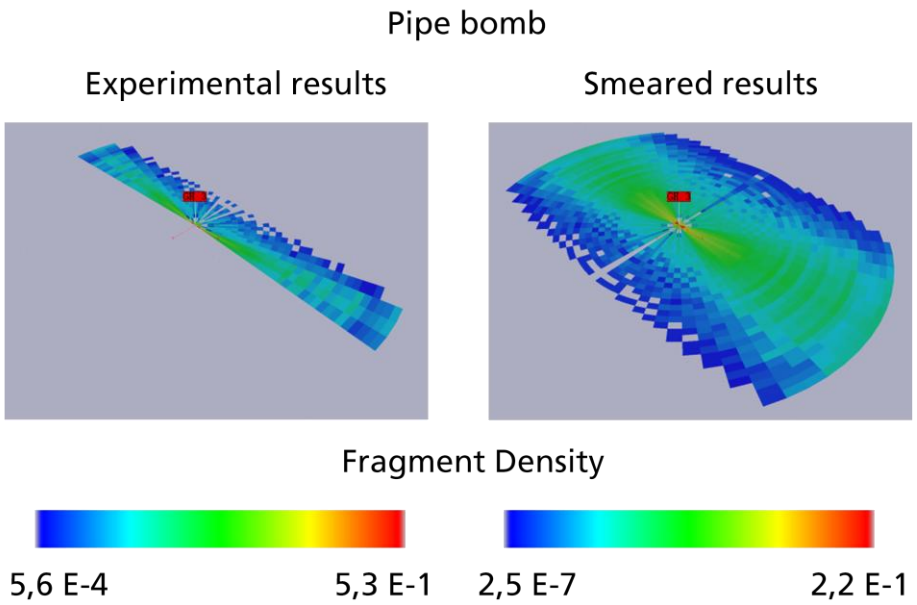

Figure 10: Comparison of the fragment density due to a small pipe bomb in the centre of the area; using experimental results (left), using smeared results (right).

It is important to be able to evaluate the influence of the smearing on the fragment matrix and finally on the potential of the hazard source characterized by the fragment

matrix. We employ characteristic quantities as mass, momentum and energy of the fragment matrix defined as

$$M_{fm} = \sum_{r,c} m_{ij} \,, \tag{6}$$

$$p_{fm} = \sum_{r,c} m_{ij} v_i \text{ and} \tag{7}$$

$$E_{fm} = \sum_{r,c} \frac{1}{2} m_{ij} v_i \,, \tag{8}$$

where r, c is the short hand for the summation over the rows and columns of the matrix, the index i indicates the row and j denotes the column. M_{fm} denotes the total mass of the fragment matrix, m_{ij} is the mass of all fragments of one mass class in one angle interval defined as

$$m_{ij} = N_{ij} m_j \,, \tag{9}$$

where m_j is the mean value of each mass class and N_{ij} denotes the number of fragments per mass class and angle interval. p_{fm} denotes the total impulse of the fragment matrix and v_i is the launch velocity of an angle interval.

Another characteristic quantity is the maximum throw distance in vacuum $x_{\max}$ calculated by

$$x_{\max} = \frac{{v_{0\max}}^2}{g} \,, \tag{10}$$

where

$$v_{0\max} = \max(v_i) \tag{11}$$

and g is the gravitational constant. Although these quantities are trivial, they help in comparing and evaluating fragment matrices.

3.2 Treatment of Barriers and Buried Sources

Another important aspect regarding IED and EOD scenarios is the treatment of buried ammunition and the influence of barriers.

When treating partially or fully buried shells, we need to consider propagation of fragments above as well as below ground. Although some fragments would certainly perforate the soil, we assume that only fragments above ground propagate. Therefore, we place a virtual, cylindrical cover around the hazard source as shown in Figure 11. First, all fragments are propagated within the cover. But only if a fragment intersects

with the cover above ground, the fragment is further propagated. Otherwise it is stopped.

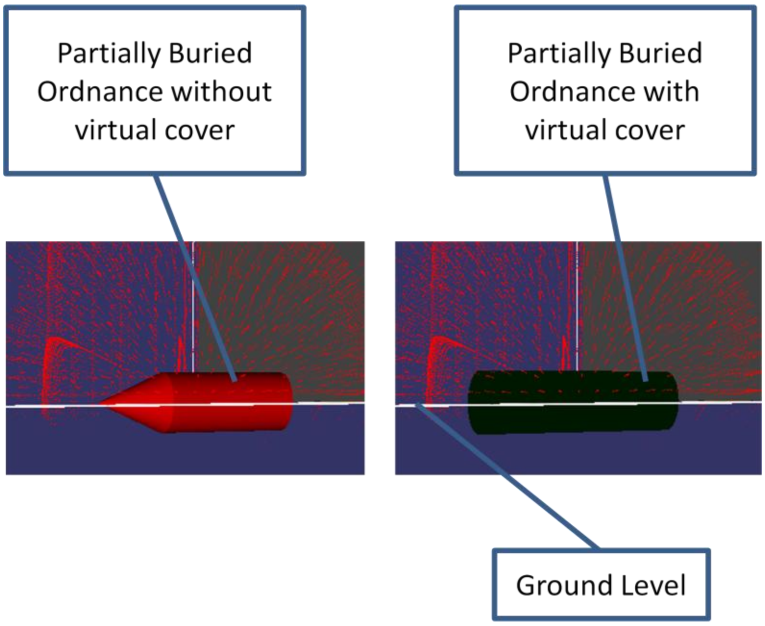

Figure 11: Treatment of ordnance partially buried below the ground using a virtual cover to determine fragment propagation.

Barriers are treated in a similar way. If a fragment hits a non-penetrable barrier it is not further propagated. To include the effect of partially penetrable barriers we extend the representative fragment approach.

Using the concept of representative fragments as explained in Section 2.2, the protective effect of barricades is included by multiplying the trajectory probability with a reduction factor $\lambda_{barrier}$ yielding

$$\lambda_{traj,barrier} = \lambda_{barrier} \cdot \lambda_{traj} \tag{12}$$

with

$$0 \le \lambda_{barrier} \le 1, \tag{13}$$

where $\lambda_{barrier}$ describes the fragment permeability of the barricade.

The effect of this approach is shown in Section 4.1. A fragment which hits a permeable barricade is not removed from the calculation but its trajectory probability is reduced and thus the fragment density behind the barricade decreases. Buildings, vehicles and helicopters are considered to block all fragments. They act like non-permeable barricades.

3.3 Damage Assessment Tailored for Explosive Ordnance Disposal Applications

After having adapted the hazard source description to the special needs of IED and EOD scenarios as well as including the description of buried hazard sources and barriers it turned out to be necessary to include some kind of consequence description allowing for fast assessment of the expected damage. Therefore, we employ damage zones for persons, buildings and infrastructure, un-armoured vehicles and aircraft as described in Table 1. We assume that an event takes place and distinguish three kinds of damage zones (DZ).

Table 1: Description of EOD Damage Zones (DZ).

Damage Zone	**Effect on**			
	Persons	Buildings/ Infrastructure	Un-armoured Vehicles	Aircrafts
A	Lethal injuries	Damaged beyond repair	Damaged beyond repair	Damaged beyond repair
B	Serious injuries	Serious damage	Damaged but still usable	Heavily damaged, not airworthy
C	Minor or no injuries	Minor or no damage	No damage	Airworthy

Damage zones for persons are based on a combination of blast and fragment hazards. The probability that a person is injured by a fragment is calculated for separate parts of the body using probits in terms of impact energy over impact area and then it is combined as for example explained in [18]. The blast injury calculations are based on the ear injury probits as described in [10]. In Table 2 the qualitative description of the models for damage zone A is given as an example.

Blast and fragment models are combined following

$$P_{DZ}(r) = \min(P_{frag}(r) + P_{blast}(r), 1), \tag{14}$$

where P_{DZ} is the probability that the event described by the damage zone, as for example "lethal injuries" (refer to Table 2), occurs, P_{frag} denotes the probability that the corresponding fragment injuries occur, P_{blast} denotes the probability of the corresponding blast injuries and r is the distance between an ES and the PES. In Figure 12 a graphical representation of a damage zone for persons is depicted.

Table 2: Description of damage zone A for persons splitted into blast and fragment injuries.

DZ	Description	Fragment	Blast
A	Probability of lethal injuries: $P_{DZ}(r)$	Probability of lethal injuries due to hits of one or more body parts: $P_{frag}(r)$	Probability that serious ear injuries occur, i.e. total destruction of the ear drum: $P_{blast}(r)$

All damage zones are implemented in the ESQRA-GE EOD as transparent layers so that it is possible to see what damage is to be expected at which point on the map. A color scheme indicates the probability of an event within the damage zone. The lower boundary of the zone is defined by a probability of 1%. Thus, outside the zone a risk smaller than 1% exists for the considered damage.

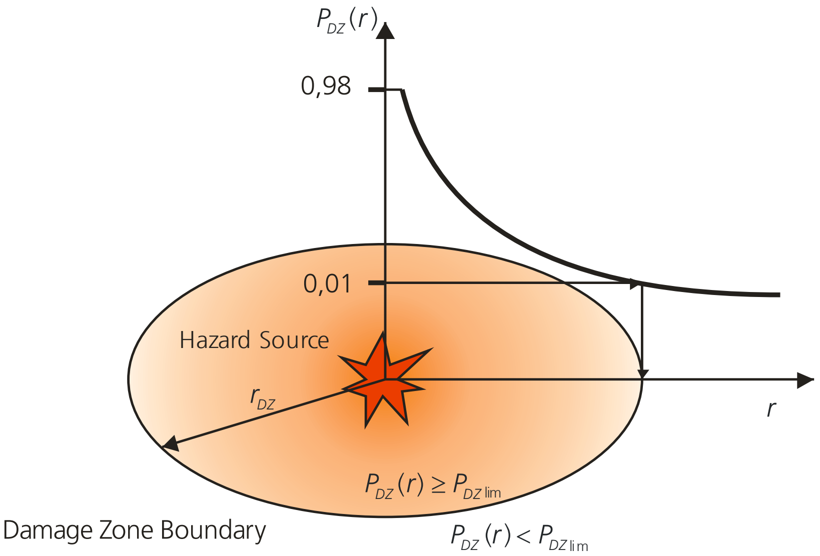

Figure 12: Graphical representation of a damage zone for persons; the colour gradient indicates the probability of an event occurring within the zone P_{DZ}, $P_{DZ\,lim}$ describes the boundary of the damage zone and r_{DZ} is the radius of the damage zone.

The damage zones for buildings, un-armoured vehicles and aircrafts are generated using operative damage models [7]. These models only provide the boundary of the zone. No information can be given on probabilities within the zones.

One problem regarding EOD applications is the small explosive quantity. Especially for buildings, only damage classes for quantities larger than 100 kg are available. When the quantity in the scenario is smaller than the lower limit quantity of the models for the damage class the range of the zone is set to a default value of 1000 m.

The concept of damage zones should help to make fast and well informed decisions which areas need to be evacuated or where protective measures can be placed most

efficiently to increase survivability of EOD forces. It is illustrated in some detail in Section 4.2.

4 Examples

We show the treatment of different types of barriers and the damage assessment using damage zones.

4.1 Treatment of Barriers

Correctly placed protective measures like barriers may increase the survivability of EOD personal. In this example we study the influence of different types of barricades on the fragment hazard.

We choose a scenario containing a barricade of 10 m length, 3 m height and a thickness of 10 cm at a distance of 1 m from the hazard source as depicted in Figure 13. As hazard source we employ a medium sized bomb (PES) with a net explosive quantity (NEQ) of approximately 100 kg TNT. To represent different types of barricades we vary the fragment permeability of the barricade in a range from 0 to 100%.

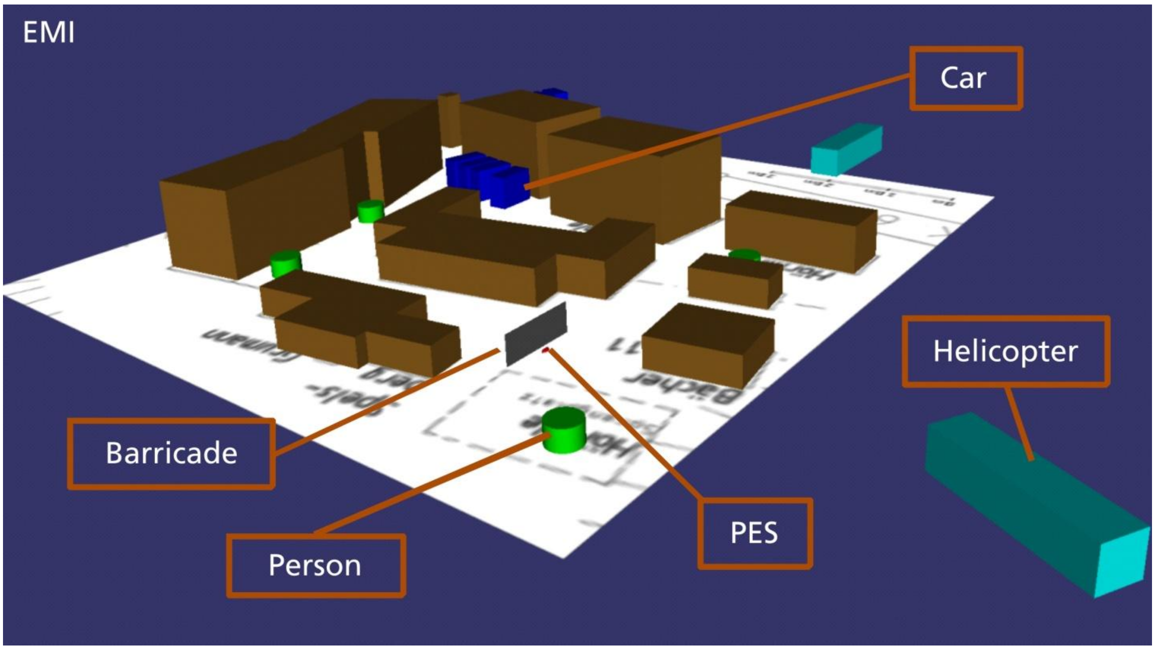

Figure 13: Scenario showing the effect of different types of barricades on fragment hazards; location: Ernst-Mach-Institute, Efringen-Krichen, Germany.

We calculate the hazard from fragments on the ground in a circle around the hazard source with a radius of 50m. We use a fine discretization in an inner circle of 25m and a coarser discretization in the outer ring to reduce computational costs.

The comparison of the results is shown in Figure 14. A Barricade that stops all fragments (100% barricade, $\lambda_{barrier} = 0$) is compared to a barricade that stops almost all fragments (90% barricade, $\lambda_{barrier} = 0.1$) and one that does not stop any fragments (0% barricade, $\lambda_{barrier} = 1$).

In the upper row of Figure 14 the fragment density on the ground within the computed 50 m radius around the hazard source is shown. Below, a zoom of the area around the barricade is plotted. The red lines in the lower part of Figure 14 indicate the fragment trajectories while the colours on the ground indicate the fragment density. The 100% barricade clearly stops all fragments. In case of the 90% barricade all fragment trajectories pass the barricade. But since we use the concept of representative fragments, each trajectory is weighted with the number of fragments launched on the representative trajectory and the probability of this trajectory. The probability of a trajectory passing through the barricades is reduced with the factor describing the permeability of the barricade. As can be seen when comparing the density on the ground behind the 90% barricade and the 0% barricade, although the same trajectories are calculated, the fragment density on the ground is clearly reduced (see shift from red to yellow close to the barrier).

This approach has the advantage that we do not need to know the exact structure of the barricade to decide which individual fragment might pass. We only need to estimate the overall quality of the barricade to reduce the fragment density if appropriate, e.g. based on expert opinion.

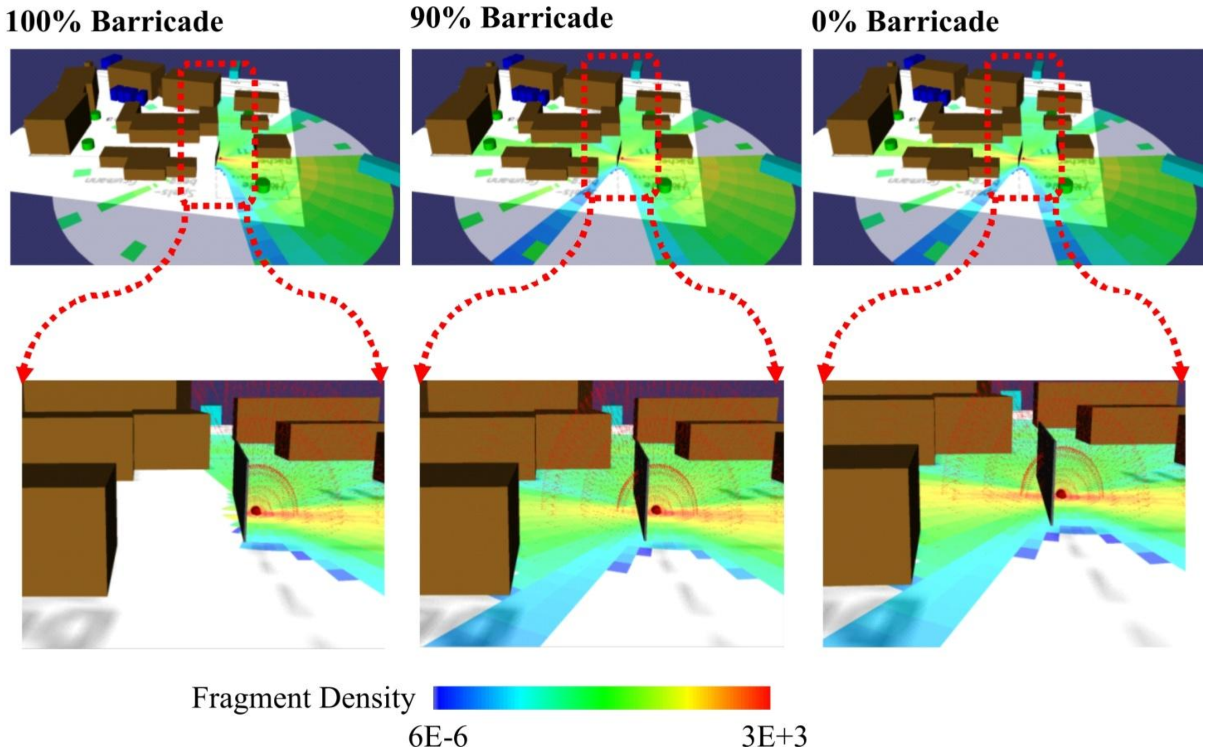

Figure 14: Comparison of the fragment density on the ground employing barricades stopping 100 %, 90 % and 0 % of the fragments; the dotted red lines in the lower row of pictures indicate the fragment trajectories.

4.2 EOD Damage Zones

In this example we illustrate the concept of damage zones. For this purpose we design a simple scenario as shown in Figure 15. A medium sized bomb (PES) with a net explosive

quantity (NEQ) of approximately 100 kg TNT is detonated in a group of three people indicated in Figure 15 as P1, P2 and P3. The bomb is placed horizontally on the ground. The persons are located at different positions with respect to the hazard source.

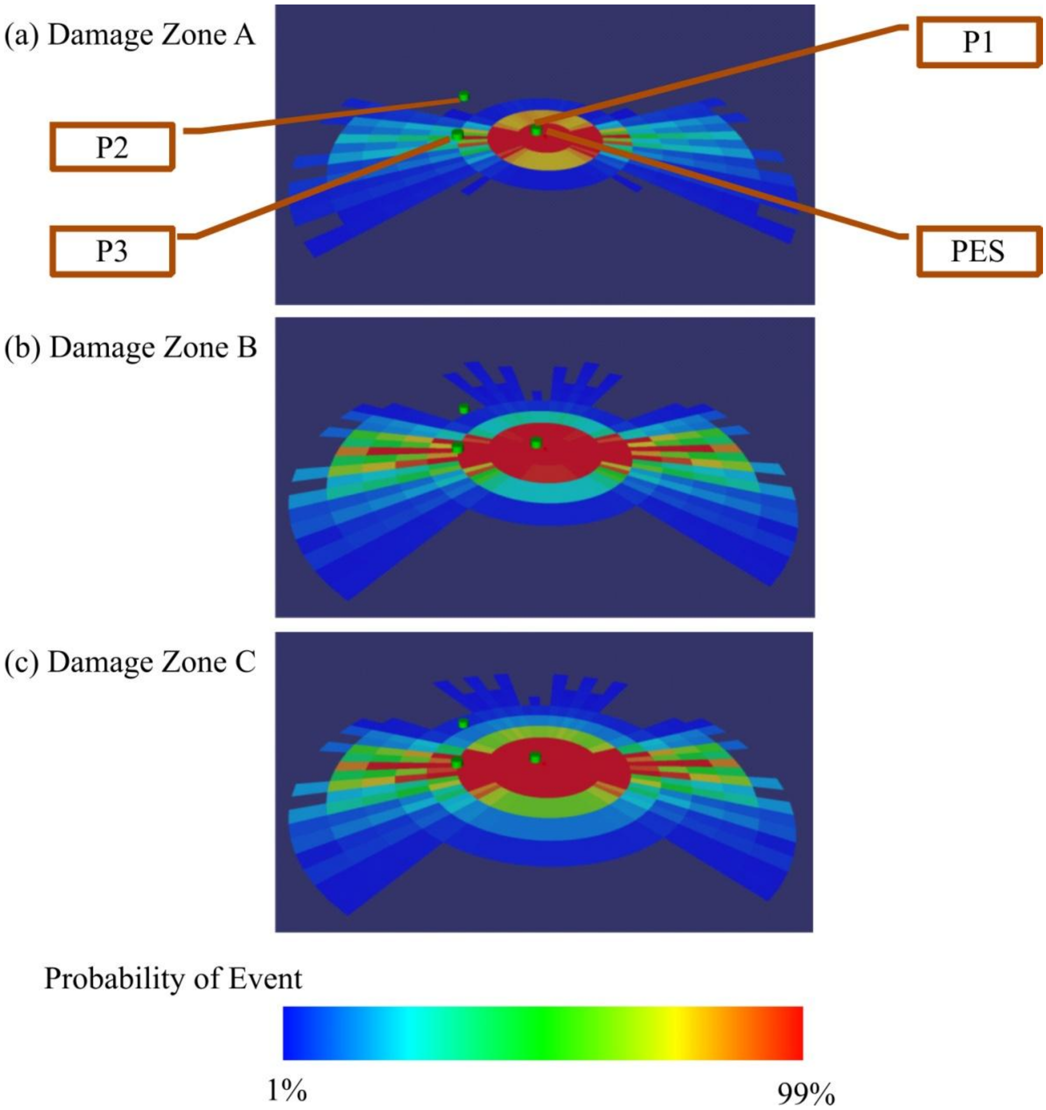

Figure 15: Comparison of damage zone A, B and C for a scenario containing a bomb as a PES and three persons (P1, P2 and P3).

In Figure 15 the output of ESQRA-GE EOD is shown. The hazard source is in the centre of each damage zone. Only person 1 and 3 are in damage zone A (lethal injuries) while Person 2 is outside zone A. But due to the inherent uncertainty in the boundary conditions as e.g. the exact position of the hazard source it is not guaranteed that Person 2 will be safe. Because of that – in addition to the graphical output – a list with information on each person is given in the software: Person 2 is listed along with Person 1 and 3 as being endangered. Persons are added to this list when their distance to the PES is smaller than the farthest boundary of the zone.

Comparing damage zones A, B and C the growth of the zones is clearly visible. It is due to the described injuries: while damage zone A describes lethal injuries, zone B covers severe injuries and zone C minor injuries.

The colour scheme indicates the probability that the specified injuries occur. This means that for example Person 2 (P2) has a probability of 1% of suffering minor injuries (refer to Figure 15 c) while Person 3 (P3) has a probability of almost 100%.

Another interesting aspect is that the cause of the injuries can be easily distinguished in the plots of the damage zones: the rings stem from blast while the finger-like parts originate from fragments.

5 Conclusions

A completely new implementation of the ESQRA-GE has been presented. Apart from featuring 3-D scenarios the model is extended to new applications as the assessment of EOD and IED scenarios.

At the moment it is still debatable at which part of an operation a software tool like the ESQRA-GE EOD could be applied. It is thinkable to use the program directly on site during a mission using previously generated scenarios of the expected area of a mission. But there are concerns that this is not possible due to time constraints.

Another possibility is to let only experts handle such a tool. If EOD troops find a disposed explosive, they can transmit the information to the expert, who in turn can provide more detailed advice than standard operating procedures do. As a result the EOD forces on site get detailed and case specific information.

The third possibility is to assess previous EOD missions and derive information from the simulation. Using this information, guidelines can be further improved.

Acknowledgements

The cooperation with the German armed forces and the Technical Centre of the German Armed Forces WTD 52, in particular Mr. Steyerer, is gratefully acknowledged. The work of Mr. Dörr, Mr. Rübarsch and Mr. Gürke on the ESQRA-GE is gratefully acknowledged as well. Furthermore we would like to thank Mr. Sättler and Dr. Hornemann for their cooperation.

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NEWEST DEVELOPMENTS IN THE GERMAN EXPLOSIVE SAFETY QUANTITATIVE RISK ANALYSIS SOFTWARE (ESQRA-GE)

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Fraunhofer
EMI

Outline

- Introduction
- Update on the ESQRA-GE
- Special issues related to EOD applications
  - Development of the ESQRA-GE EOD
- Conclusions

ESQRA-GE: Ammunition Storage Scenarios

Ammunition storage facility
Source: Vortragswesen BW

Accident in an ammunition storage facility
Albania, 2008/03/15,
Source: Wiki

Use of risk analysis tools

Risk Analysis Scheme

Threat scenario

Physical hazards
Damage / Consequences

Hazard and damage analysis

Exposure

Event frequency

Probability analysis

Risk
per year, per event, individual, group

Reference risk

Risk communication

Risk analysis

Protection measures

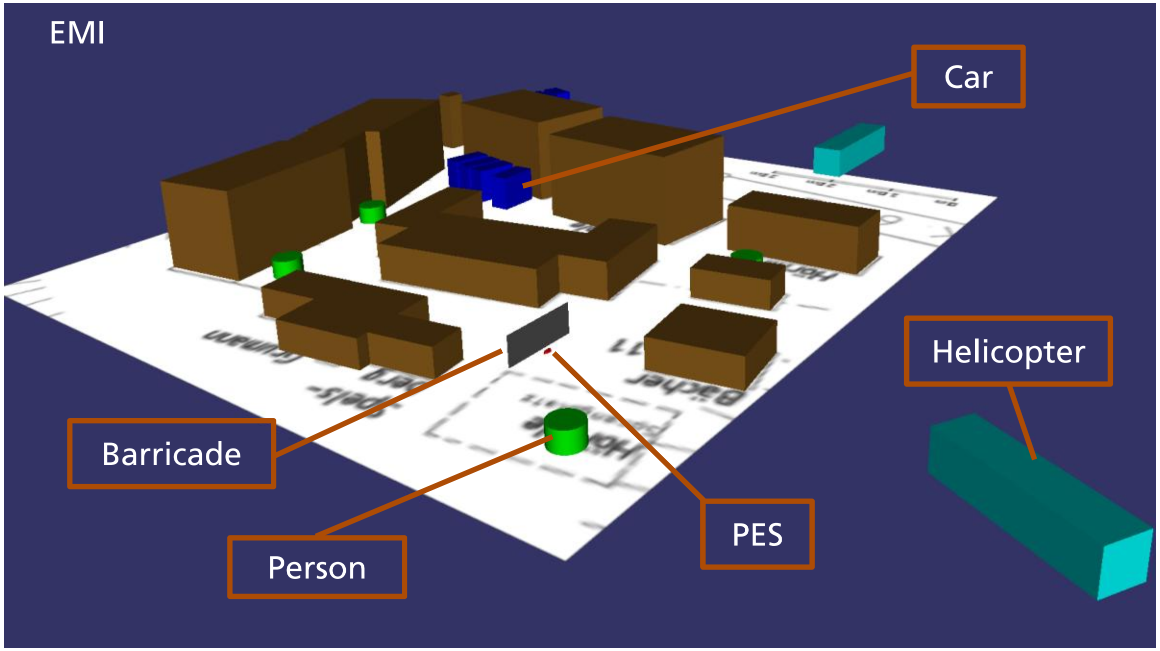
Risk minimization

Accept or change scenario

Risk management

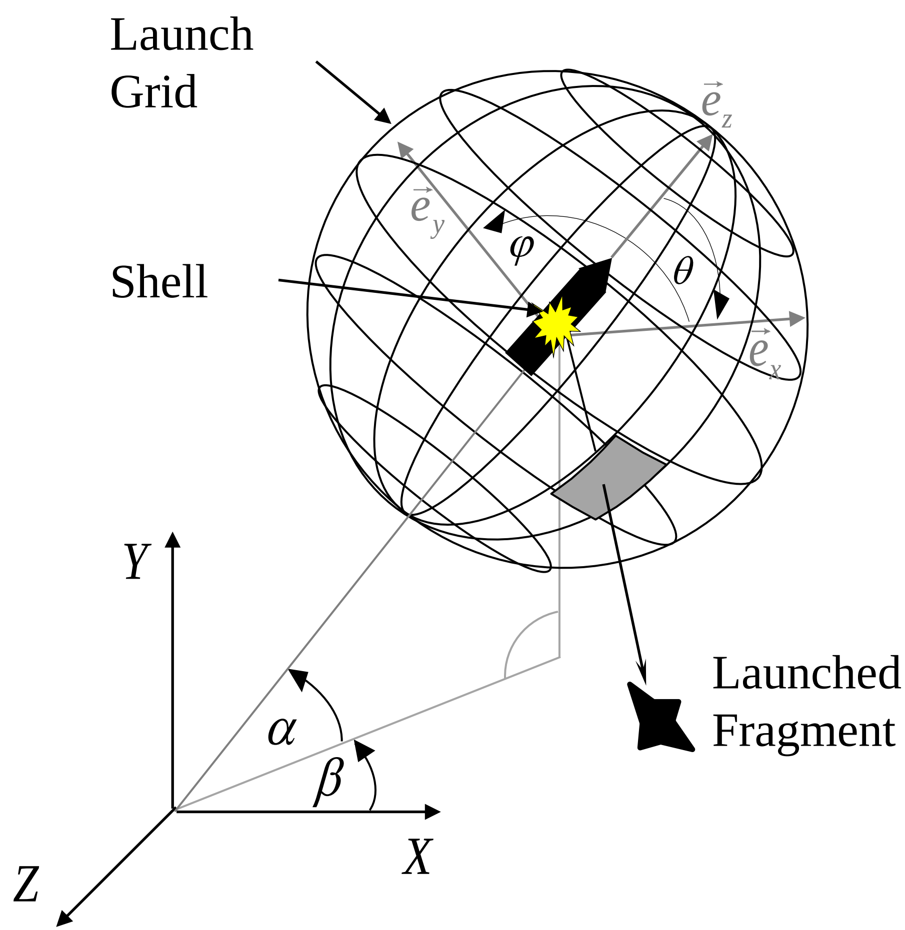
Scenario Definition

- 3D View
- Map can be added
- Objects can be placed using drag and drop
- Arbitrarily placed PES

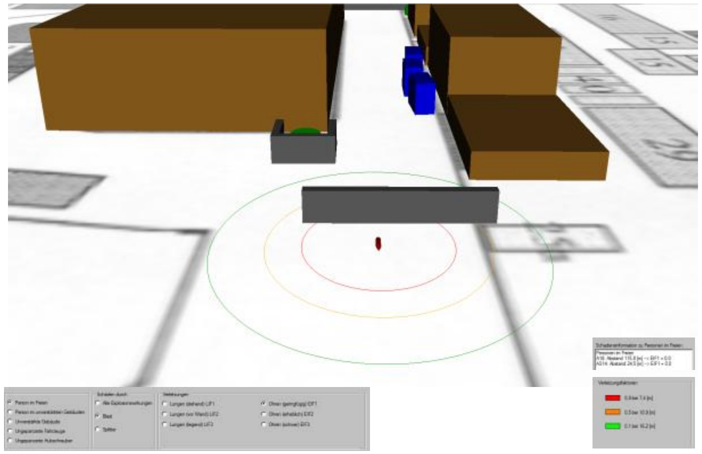


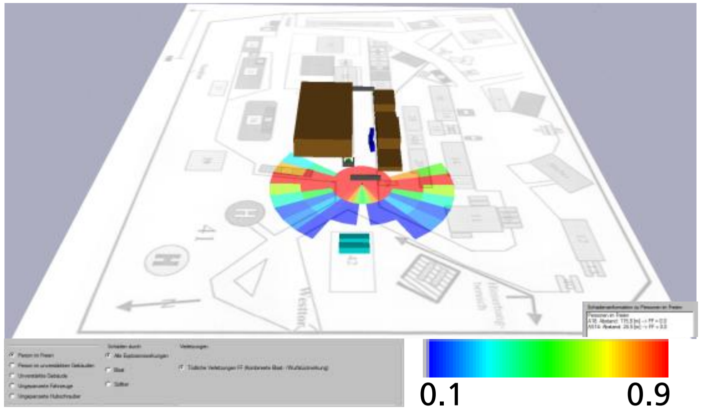
Hazard Analysis

- Blast effects (Kingery Bulmash polynomials)
- Fragment and Debris throw
  - Point Source
  - Propagated through unit sphere
  - Point mass
  - Basically two dimensional model
  - Gravity
  - Drag force



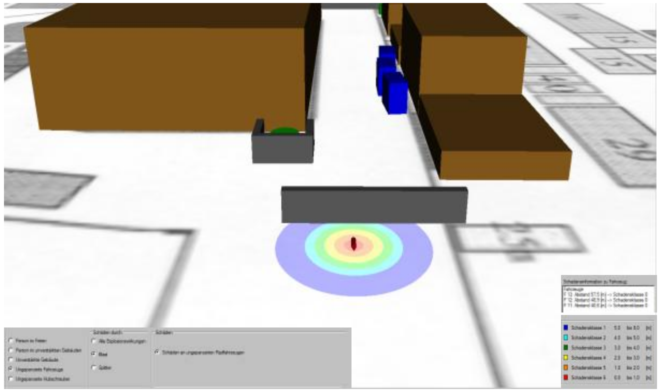
Consequence Analysis





Probability of fatalities due to blast and fragments

Probability of minor ear injuries due to blast



Vehicle damage due to blast

Operative damage models (damage classes 1 to 6)

Fraunhofer EMI

Extension to EOD and IED Applications

EOD, Northern Ireland
Source: Wikipedia

Car Bombing in Iraq
Source: Wikipedia, J.Gordon

Use of risk analysis tools

ESQRA-GE: Explosive Ordnance Disposal Scenarios

Context of use of the ESQRA-GE EOD

- Assessment of EOD scenarios
- Decision on possible evacuation of people
- Placement of protective measures like barricades

Boundary conditions:

- Undefined scenarios
- Uncontrolled situations
- Time restrictions

Risk Analysis Scheme

Threat scenario

Physical hazards
Damage / Consequences

Exposure

Event frequency

Risk
per year, per event, individual, group

Reference risk

Protection measures

Accept or change scenario

Hazard and damage analysis

Probability analysis

Risk communication

Risk minimization

Risk analysis

Risk management

Hazard Source Characterization

- Amount of explosive
- Fragment matrix
- ➢ Characterization of the hazard source

Angle intervals [deg]

Mass intervals [kg]

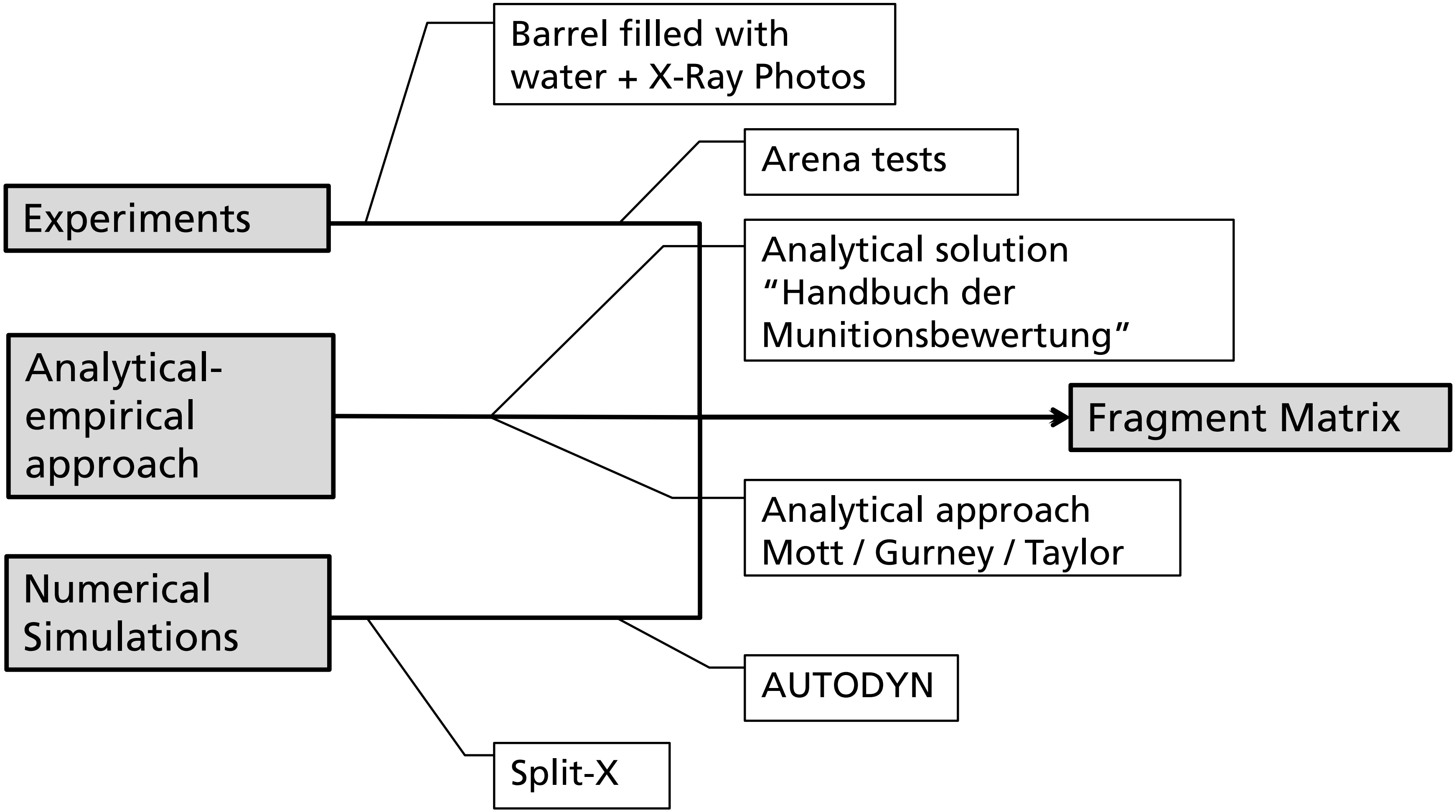
```
18      15
        0.0002  0.00032  0.00056  0.001  0.0018  0.0032  0.0056  0.01  0.018  0.032  0.056  0.1  0.18  0.32  0.56
10
20
30
40
50
60
70
80
90                        55                                                                             1073
100
110
120
130
140
150
160
170
180
```

Fragment number [-] per mass and angle interval

Max launch velocity [m/s] per angle interval

Fraunhofer EMI

Approaches to Generate Fragment Matrices

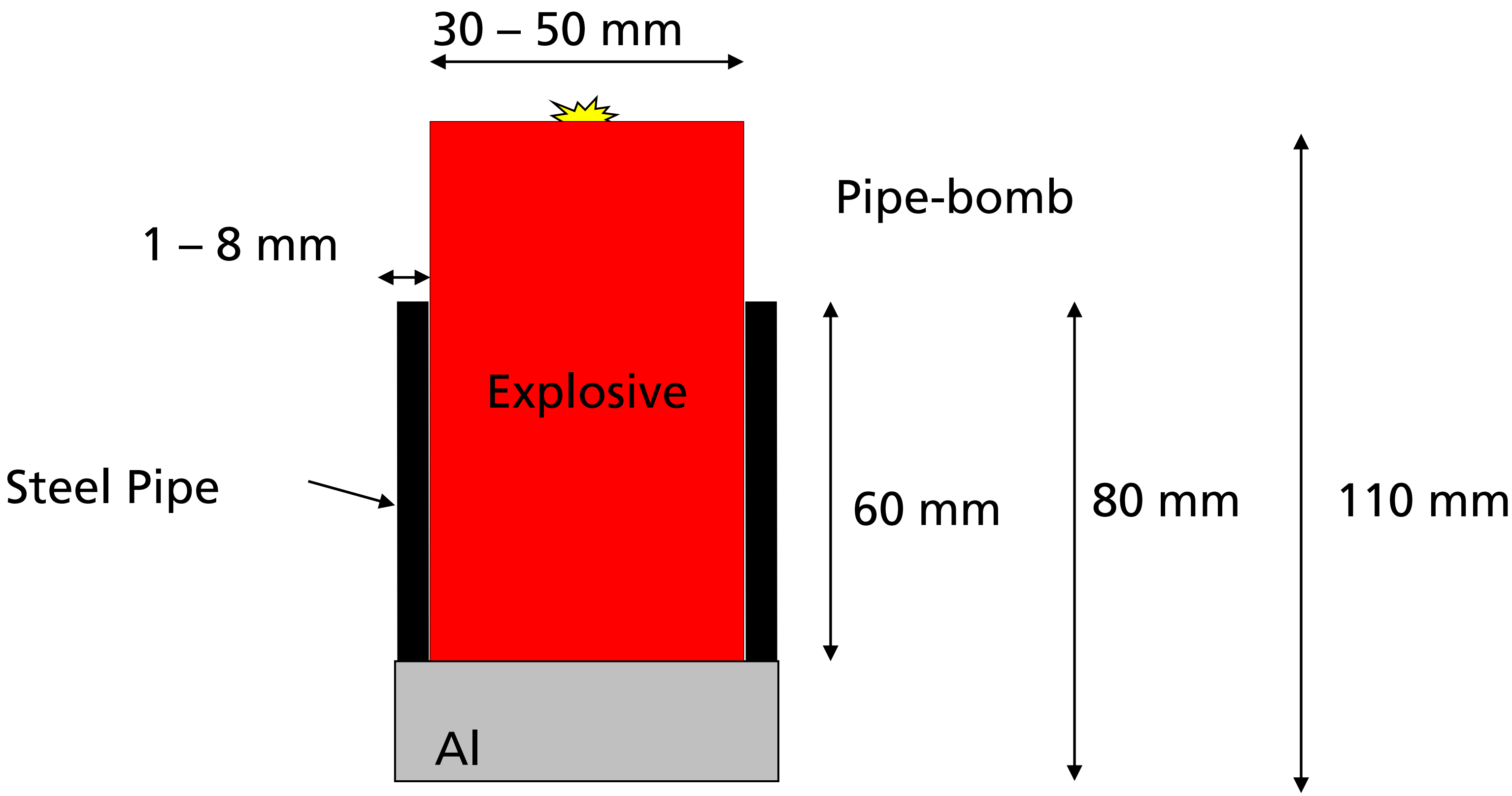


Pipe bombs – Analytical – Experimental Approach

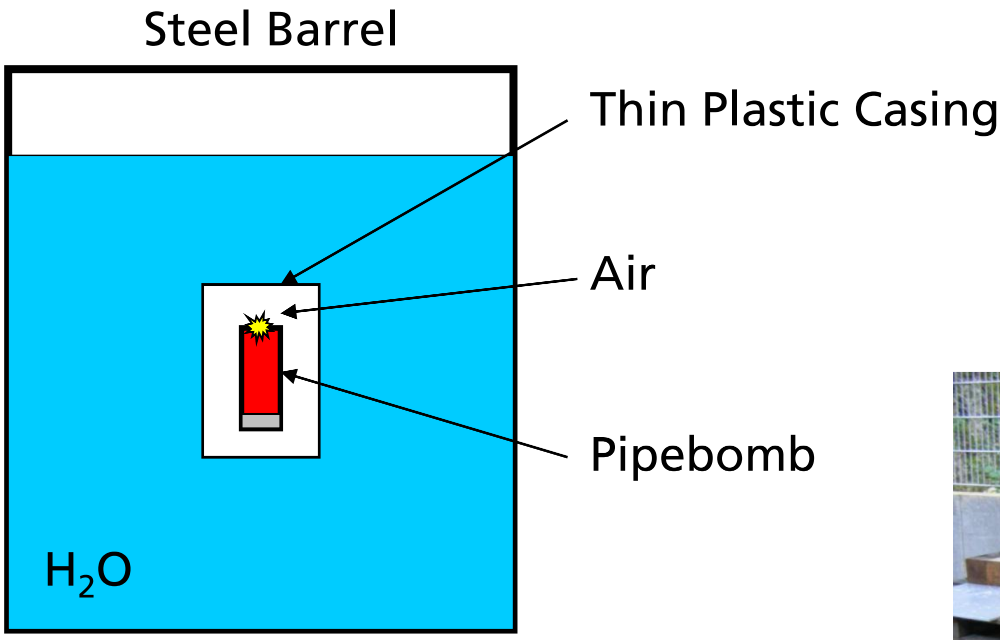
Geometry					
diameter [mm]	length [mm]	wall thickness [mm]	explosive	expriments X-Ray	experiments in Barrel
30	60	1	PETN	2 - 3	3
30	60	2	PETN	2 - 3	3
30	60	4	PETN	2 - 3	3
30	60	8	PETN	2 - 3	3
30	60	1	ANFO	3	3
30	60	2	ANFO	3	3
30	60	4	ANFO	3	3
30	60	8	ANFO	3	3
40	60	1	ANFO	3	3
40	60	2	ANFO	3	3
40	60	4	ANFO	3	3
40	60	8	ANFO	3	3
40	60	1	Gunpowder	3	3
40	60	2	Gunpowder	3	3
40	60	4	Gunpowder	3	3
40	60	8	Gunpowder	2 - 3	3
50	60	1	ANFO	3	3
50	60	2	ANFO	3	3
50	60	4	ANFO	3	3
50	60	8	ANFO	3	3
50	60	1	Gunpowder	3	3
50	60	2	Gunpowder	3	3
50	60	4	Gunpowder	3	3
50	60	8	Gunpowder	2 - 3	3

Fraunhofer EMI

Pipe bombs

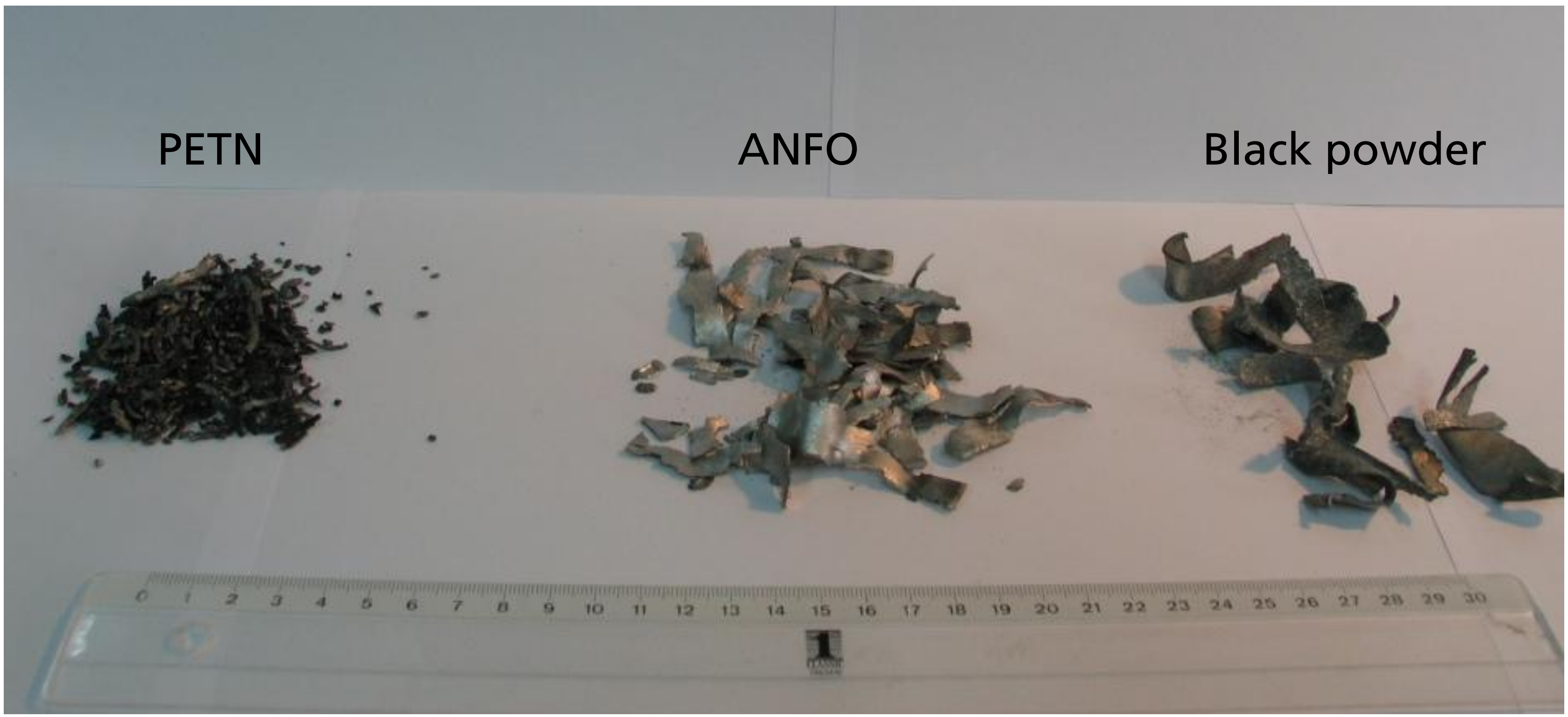

30 – 50 mm
Pipe-bomb
1 – 8 mm
Explosive
Steel Pipe
60 mm
80 mm
110 mm
Al

Water Barrel Test Setup – Mass Distribution

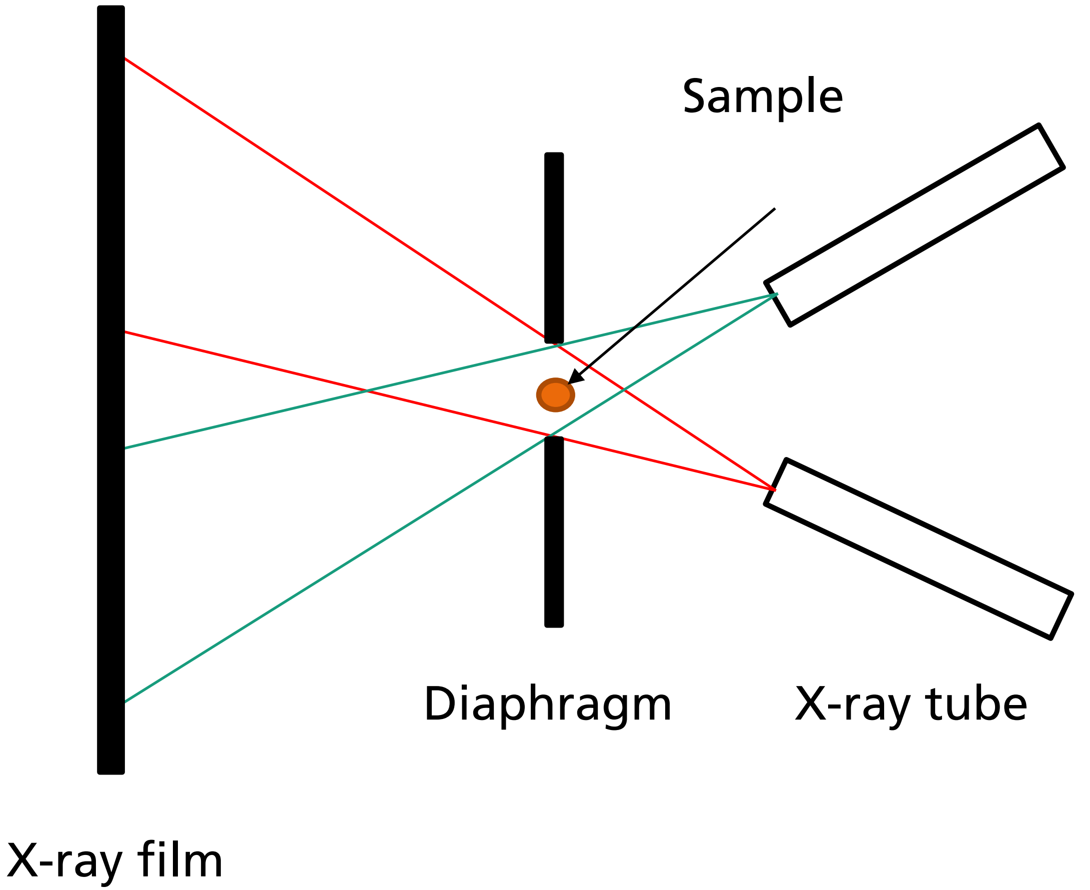


Water Barrel Tests – Results

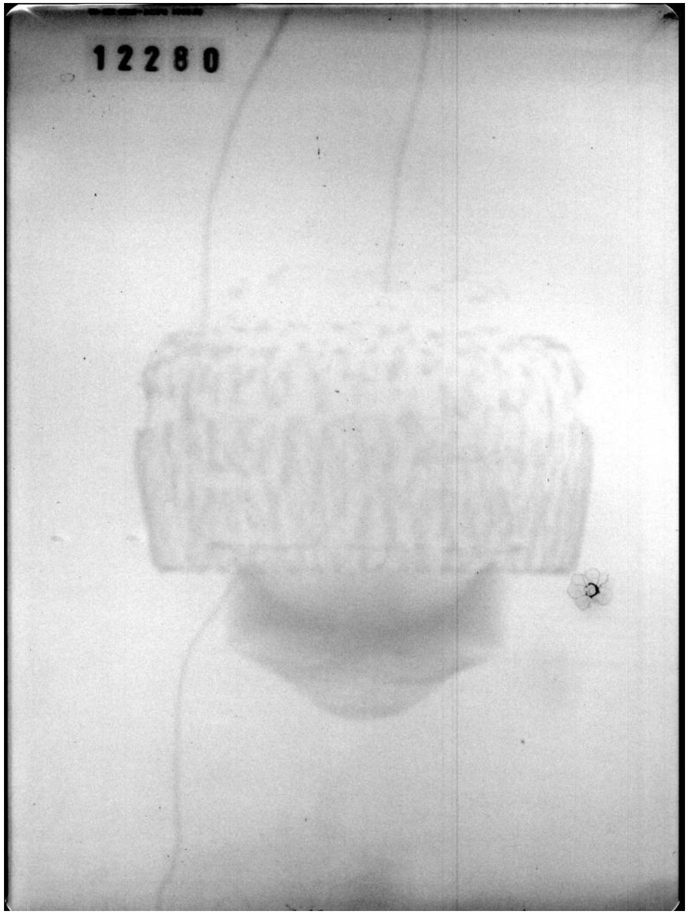
- Pipe, d=30mm, t=1mm,
- Seismoplast (PETN)(left), ANFO (middle), black powder (right),
- Experiments 12144, 12159, 12179

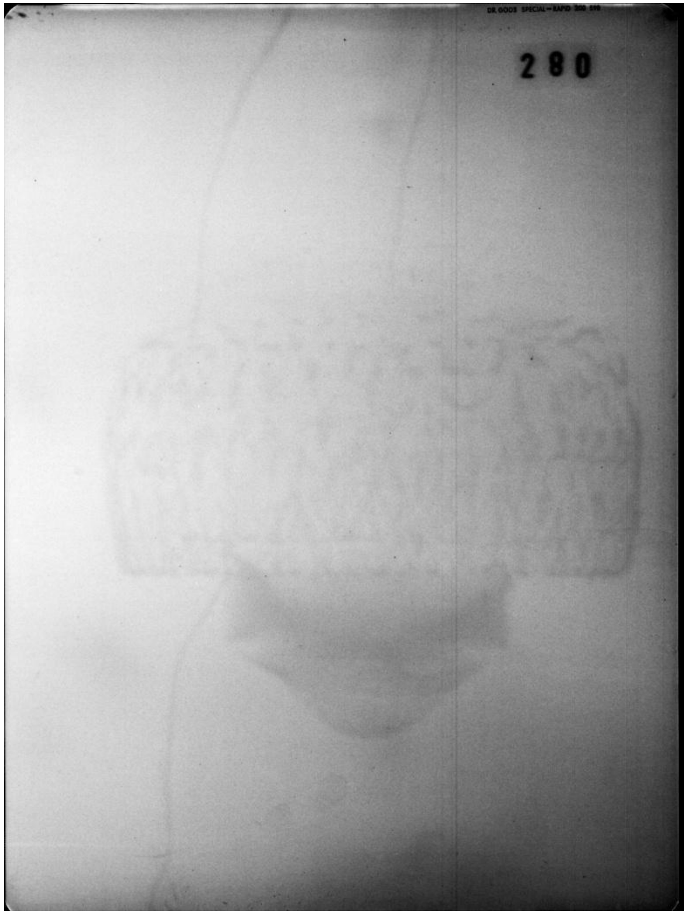


X-Ray Test Setup – Launch Velocity – Launch Angle



Pipe Bombs – Results From X-Ray Tests





PETN, d = 30 mm, t = 1mm (12280), v = 2000 m/s

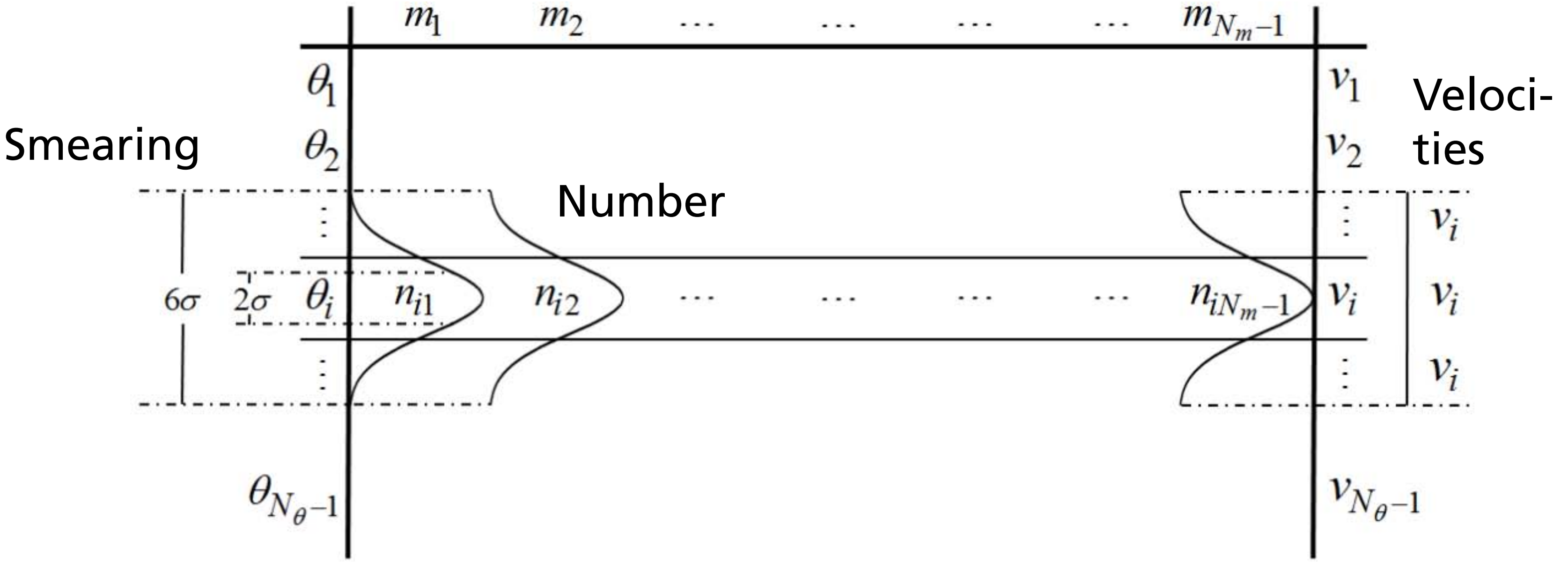
Pipe Bombs – Results From X-Ray Tests

Versuchsnummer	Datum	Sprengstoff	Ladung [g]	Booster [g]	Länge	nnendurchmesse	Wandstärke
12192	05.11.2009	ANFO	46	8	60	30	2
12284	18.02.2010	ANFO	46	8	60	30	1
12285	19.02.2010	ANFO	46	8	60	30	1
12286	19.02.2010	ANFO	46	8	60	30	2
12287	22.02.2010	ANFO	46	8	60	30	4
12288	22.02.2010	ANFO	46	8	60	30	4
12187	04.11.2009	Seismoplast	64	-	60	30	2
12188	05.11.2009	Seismoplast	64	-	60	30	4
12189	05.11.2009	Seismoplast	64	-	60	30	1
12190	05.11.2009	Seismoplast	64	-	60	30	4
12280	17.02.2010	Seismoplast	64	-	60	30	1
12281	17.02.2010	Seismoplast	64	-	60	30	2
12282	18.02.2010	Seismoplast	64	-	60	30	4
12283	18.02.2010	Seismoplast	64	-	60	30	8
12191	05.11.2010	Seismoplast	64	-	60	30	8
12289	22.02.2010	ANFO	86	8	60	40	1
12290	23.02.2010	ANFO	86	8	60	40	1
12291	23.02.2010	ANFO	86	8	60	40	2
12292	23.02.2010	ANFO	86	8	60	40	2
12299	25.02.2010	ANFO	137	8	60	40	4
12300	25.02.2010	ANFO	137	8	60	40	4
12293	23.02.2010	ANFO	137	8	60	50	1
12294	24.02.2010	ANFO	137	8	60	50	1
12295	24.02.2010	ANFO	137	8	60	50	2
12296	24.02.2010	ANFO	137	8	60	50	2
12297	24.02.2010	ANFO	137	8	60	50	4
12298	25.02.2010	ANFO	137	8	60	50	4
12301	25.02.2010	ANFO	137	8	60	50	4
12302	26.02.2010	Schwarzpulver	112	8	60	40	1
12303	26.02.2010	Schwarzpulver	112	8	60	40	1
12304	01.03.2010	Schwarzpulver	172	8	60	50	1
12305	01.03.2010	Schwarzpulver	172	8	60	50	1

Pipe Bombs – Results From X-Ray Tests

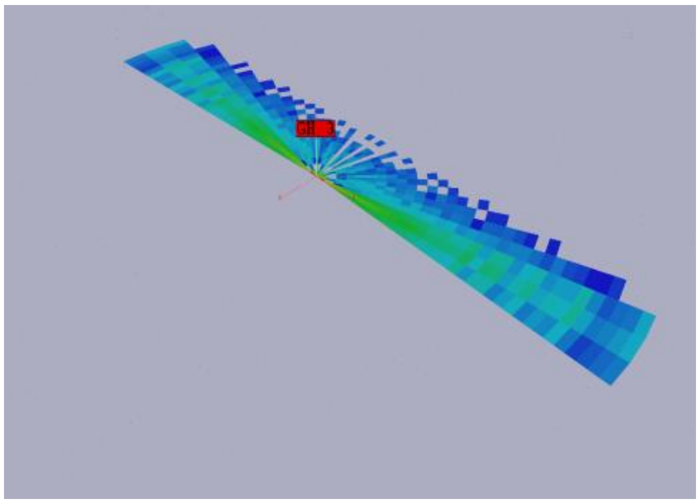
						Ausdehnung				
Versuchsnummer	Datum	Sprengstoff	t1 [us]	t2 [us]	t2-t1	t2 [mm]	t1 [mm]	Abstand [mm]	V [m/s]	
12192	05.11.2009	ANFO	160	240	80			0	0	Zeit zu lang
12284	18.02.2010	ANFO	75	125	50	300	180	120	706	
12285	19.02.2010	ANFO	75.2	115.2	40	302	204	98	721	
12286	19.02.2010	ANFO	75	105	30	192	140	52	510	
12287	22.02.2010	ANFO	80	120	40	135	103	32	235	
12288	22.02.2010	ANFO	130	170	40	135	117	18	132	
12187	04.11.2009	Seismoplast	25	50	25	276	124	152	1788	
12188	05.11.2009	Seismoplast	30	45	15	245	153	68	1333	
12189	05.11.2009	Seismoplast	30	35	5	223	187	36	2118	
12190	05.11.2009	Seismoplast	35	50	15	213	145	68	1333	
12280	17.02.2010	Seismoplast	30	35	5	236	202	34	2000	
12281	17.02.2010	Seismoplast	30	45	15	255	163	92	1804	
12282	18.02.2010	Seismoplast	35	50	15	218	154	64	1255	
12283	18.02.2010	Seismoplast	40	55	15	177	140	37	725	
12191	05.11.2010	Seismoplast	40	55	15	160	123	37	725	
12289	22.02.2010	ANFO	75.3	105.2	29.9	290	219	71	698	?
12290	23.02.2010	ANFO	65	95.4	30.4	263	180	83	803	
12291	23.02.2010	ANFO	65	95	30	198	140	58	569	
12292	23.02.2010	ANFO	75	105	30	234	167	67	657	
12299	25.02.2010	ANFO	120	150	30	216	173	43	422	
12300	25.02.2010	ANFO	120	170	50	263	186	77	453	
12293	23.02.2010	ANFO	55.2	85.4	30.2	268	176	92	896	
12294	24.02.2010	ANFO	55.2	85.4	30.2	272	179	93	906	
12295	24.02.2010	ANFO	55.2	85.4	30.2	212	148	64	623	
12296	24.02.2010	ANFO	55	85	30	227	162	65	637	
12297	24.02.2010	ANFO	150	230	80			0	0	Zeit zu lang
12298	25.02.2010	ANFO	120	150	30	248	200	48	471	
12301	25.02.2010	ANFO	120	150.4	30.4	272	218	54	522	
12302	26.02.2010	Schwarzpulver	100	140	40	200	164	36	265	
12303	26.02.2010	Schwarzpulver	100	160	60	185	146	39	191	
12304	01.03.2010	Schwarzpulver	100	150	50	268	195	73	429	
12305	01.03.2010	Schwarzpulver	100	150	50	220	170	50	294	

Analytical Treatment of the Experimental Fragment Matrix

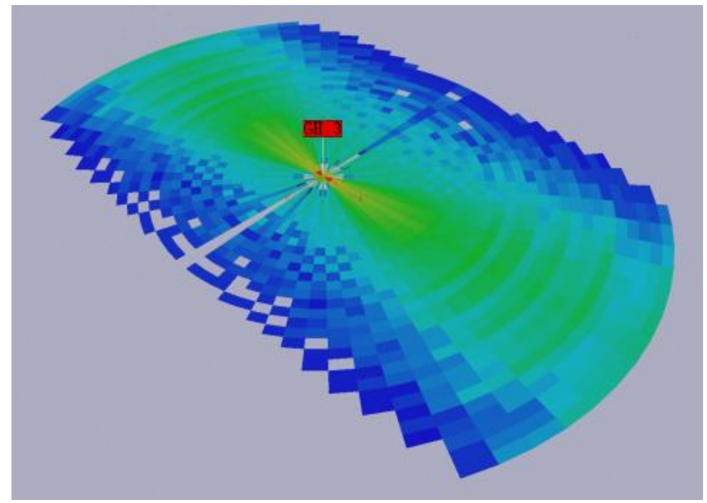


Smeared Pipe Bomb

Experimental results



Smeared results



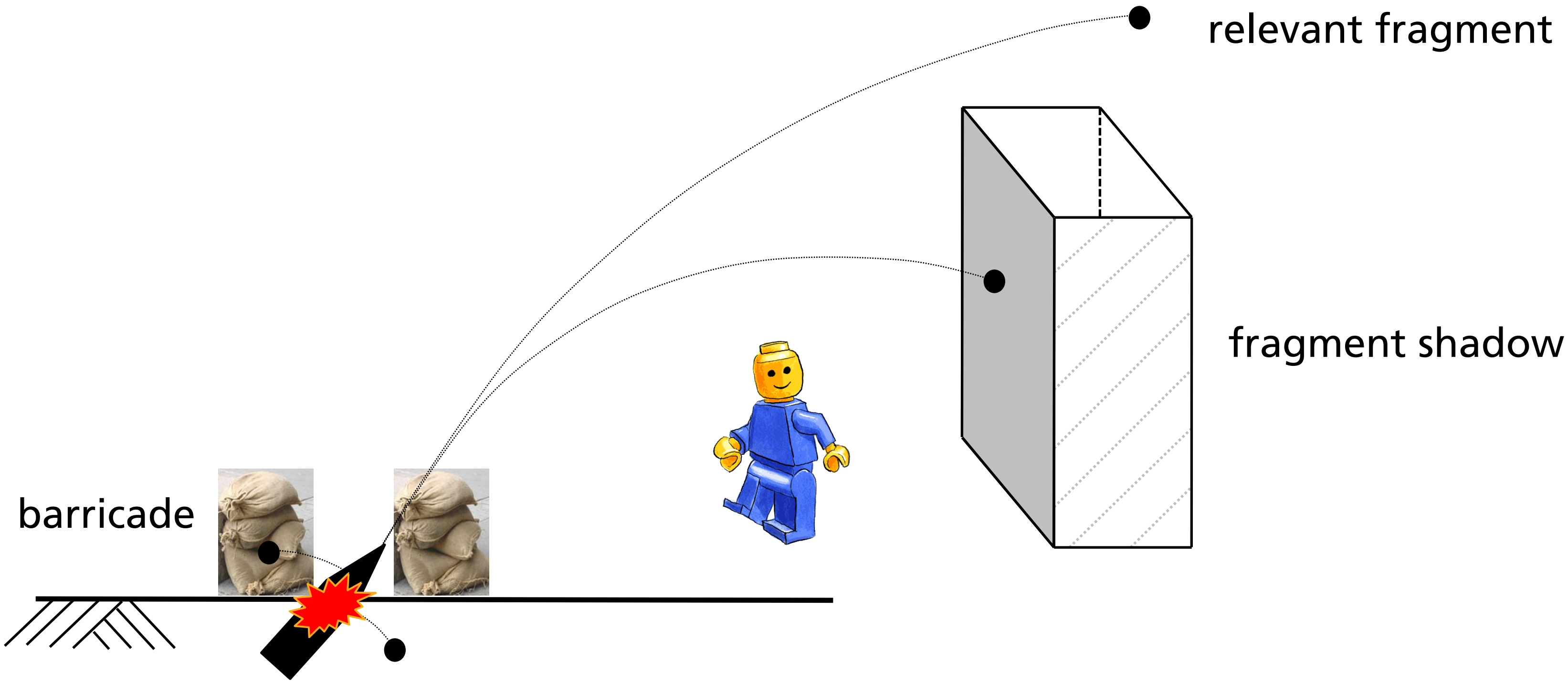
Fragment Density

5,6 E-4 5,3 E-1

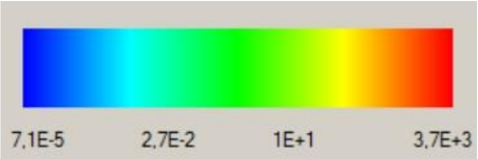
2,5 E-7 2,2 E-1

Treatment of Protective Measures

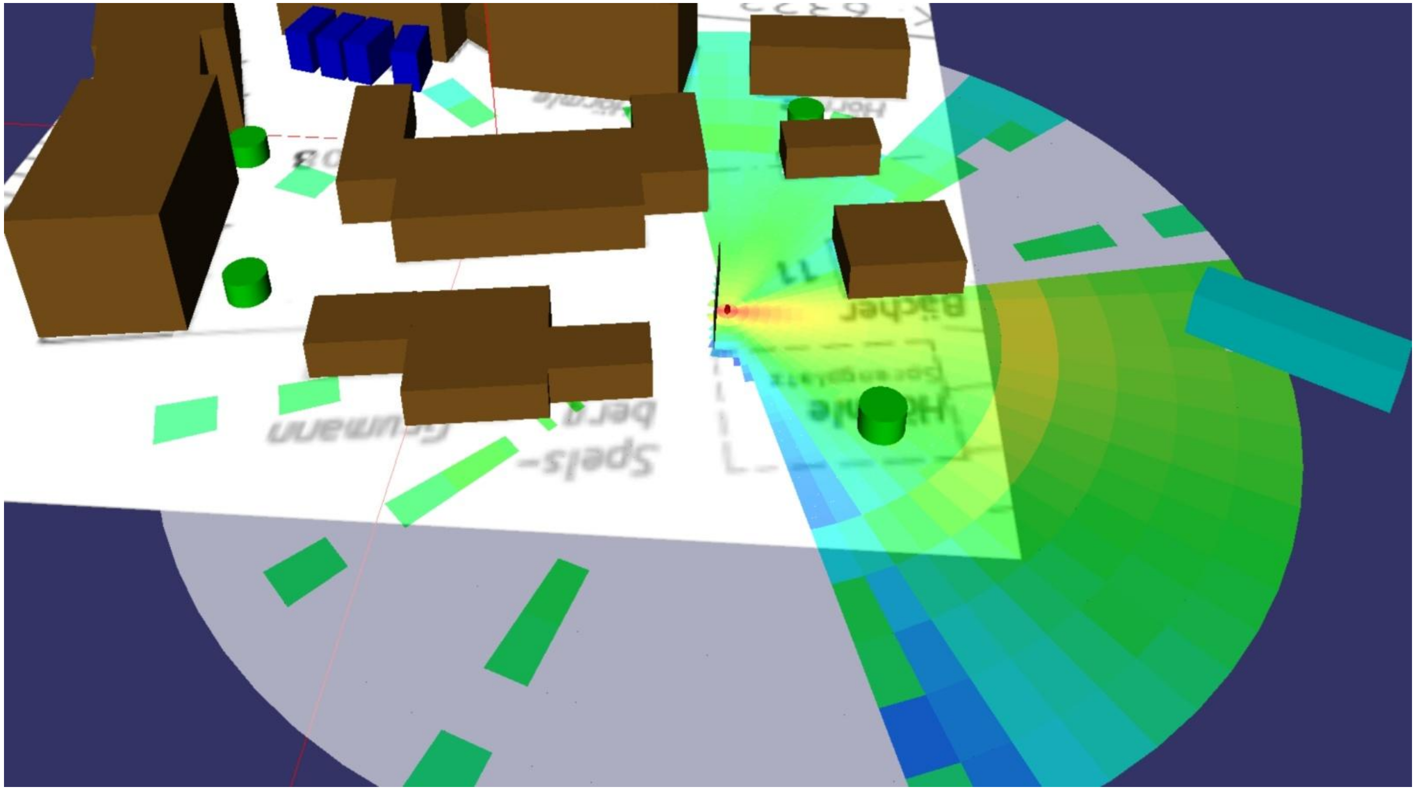
- Based on geometrical consideration
- Use of advanced computational geometry -- Open Scene Graph



Protective Measures – 100% Barricade

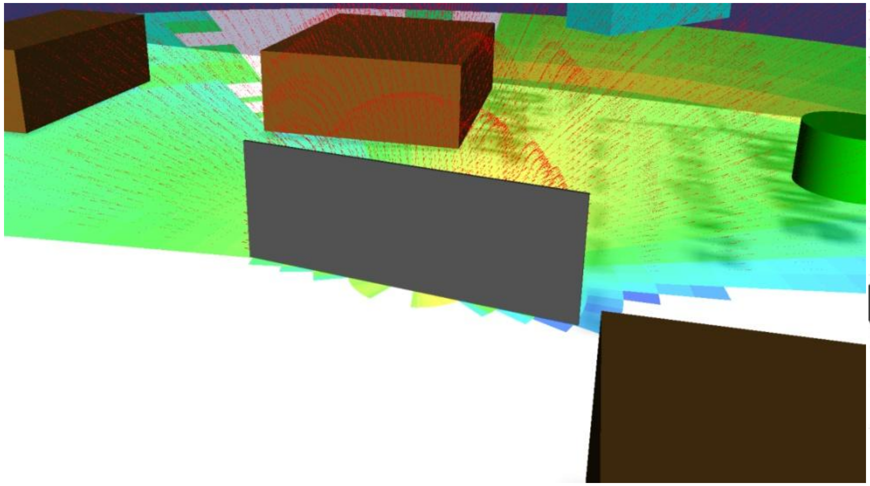


Full view of scenario

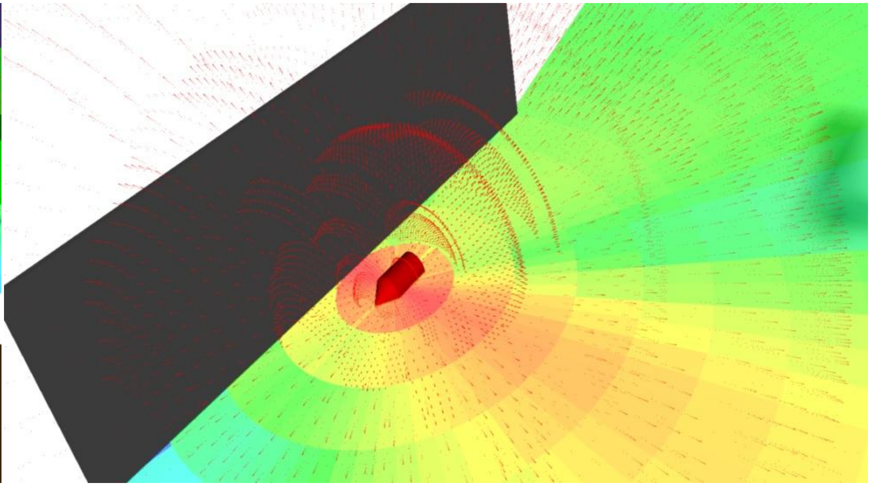


Protective Measures – 100% Barricade

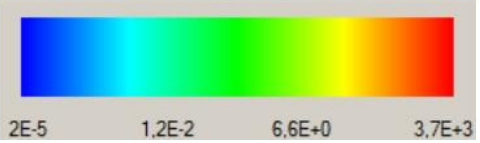
Behind barricade



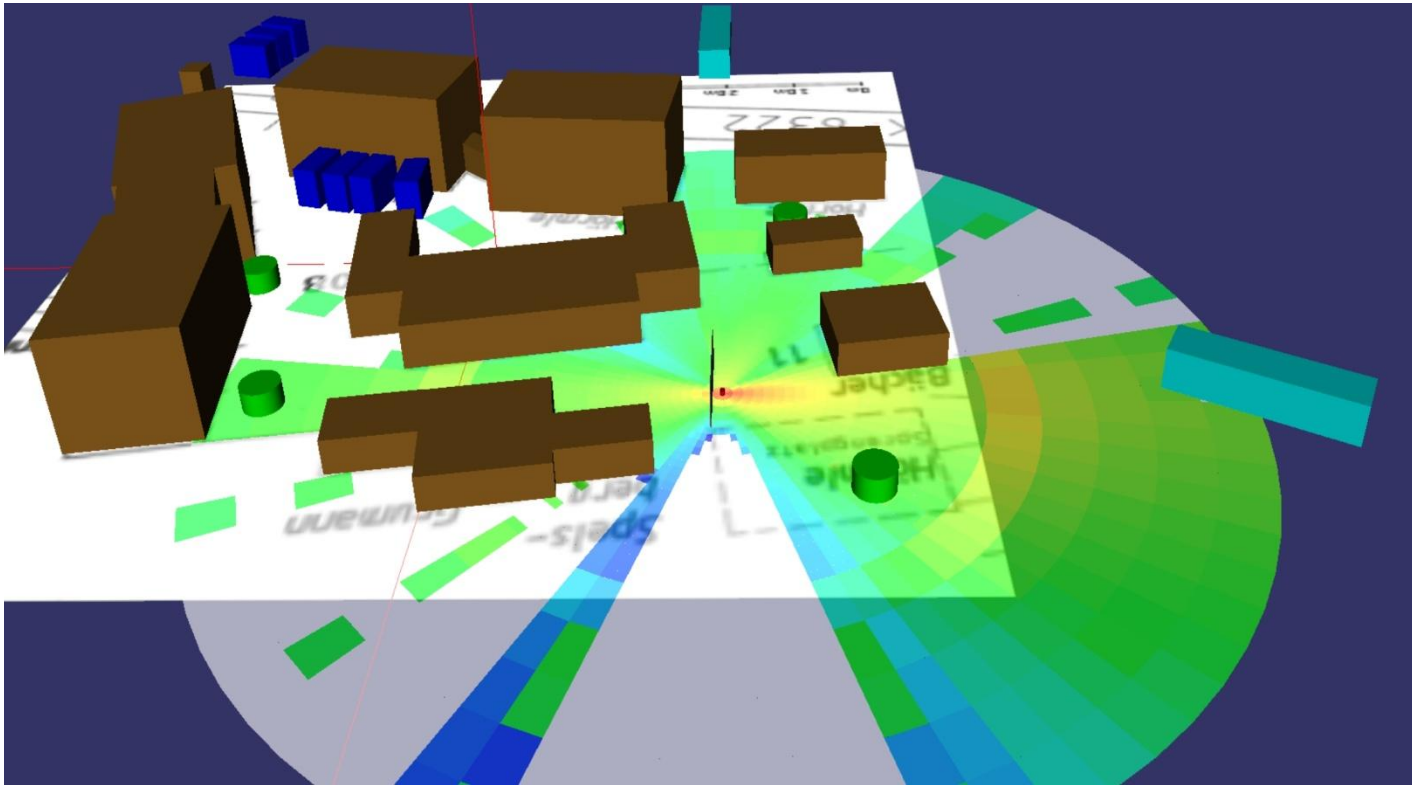
In front of barricade



Protective Measures – 90% Barricade

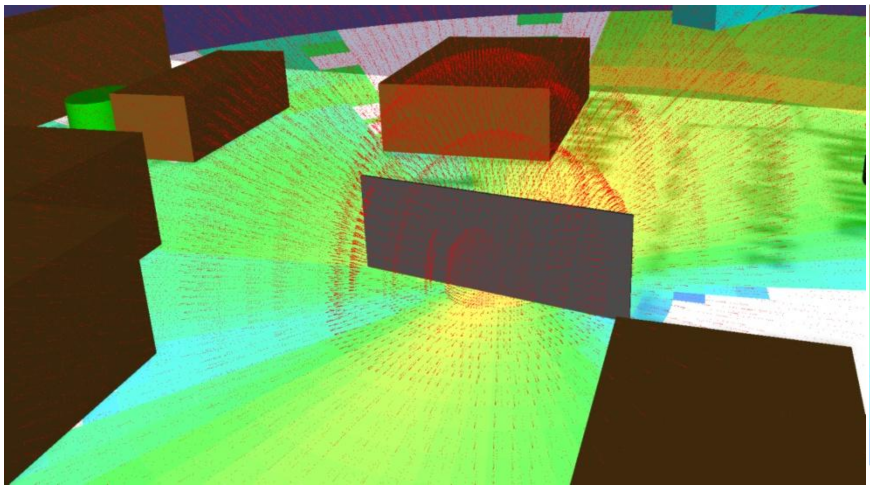


Full view of scenario

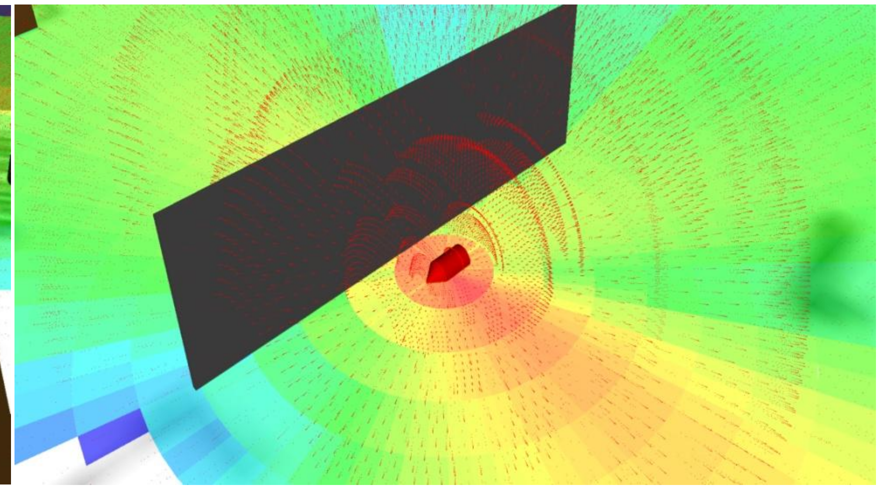


Protective Measures – 90% Barricade

Behind barricade

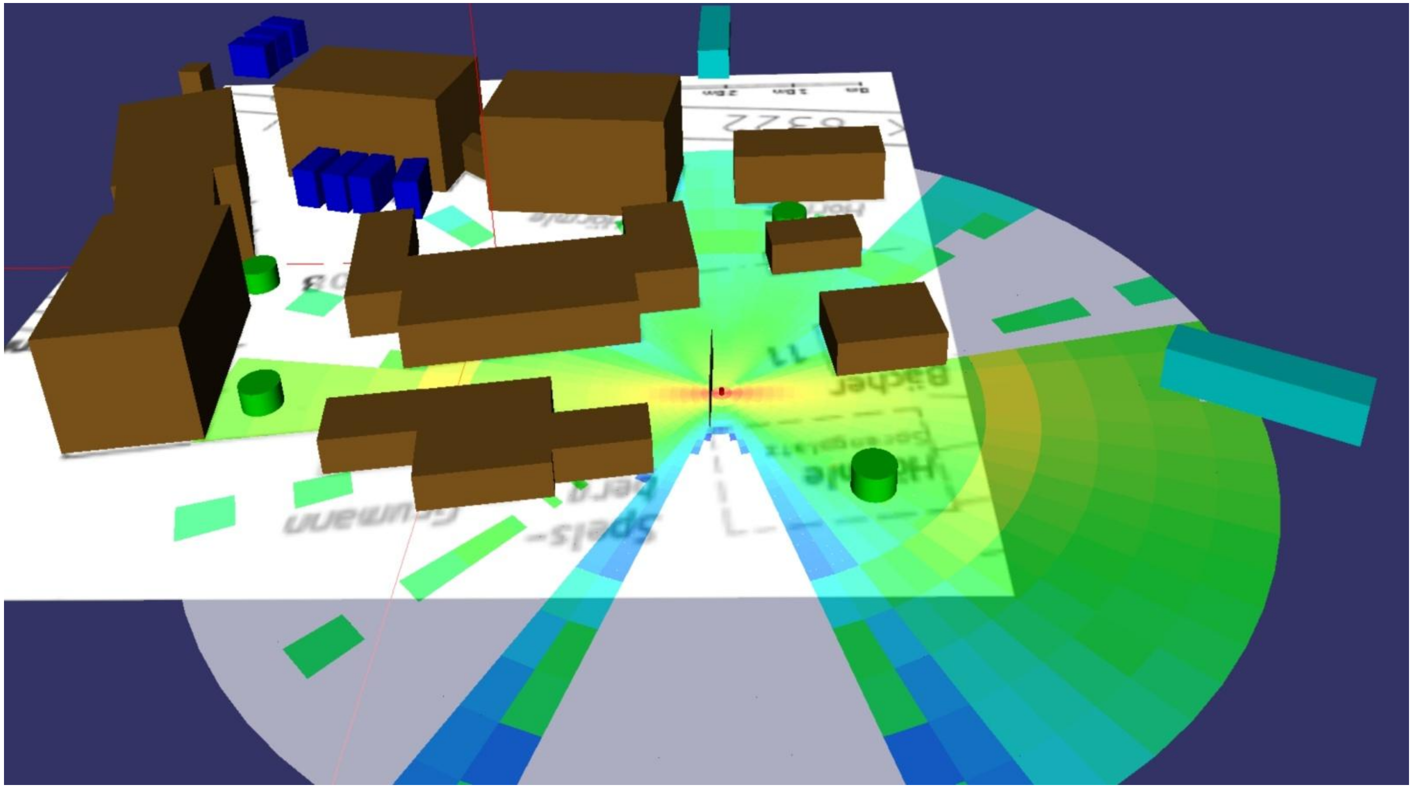


In front of barricade



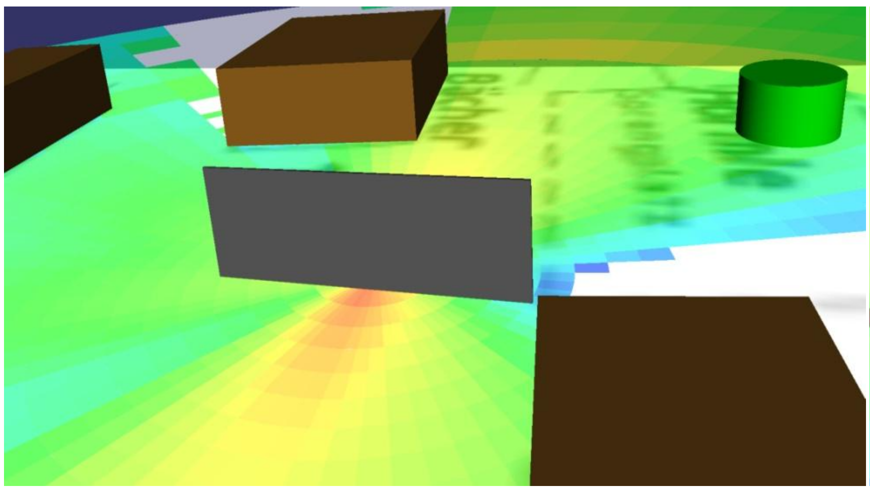
Protective Measures – 0% Barricade

Full view of scenario

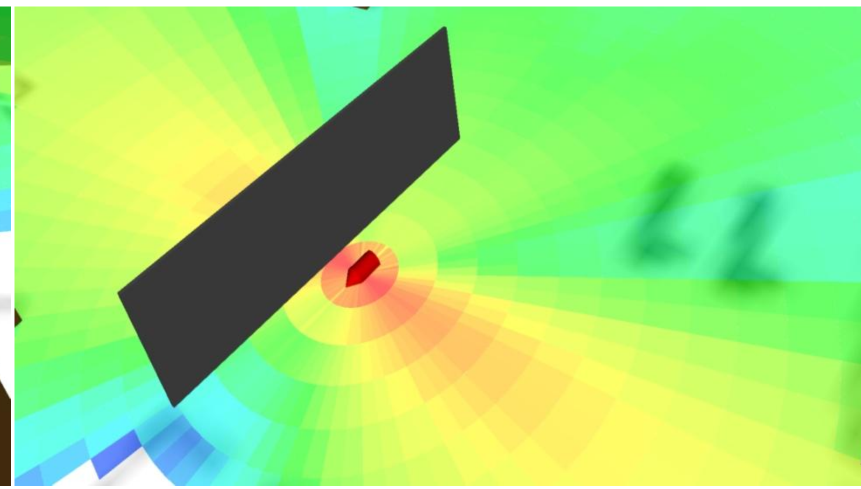


Protective Measures – 0% Barricade

Behind barricade



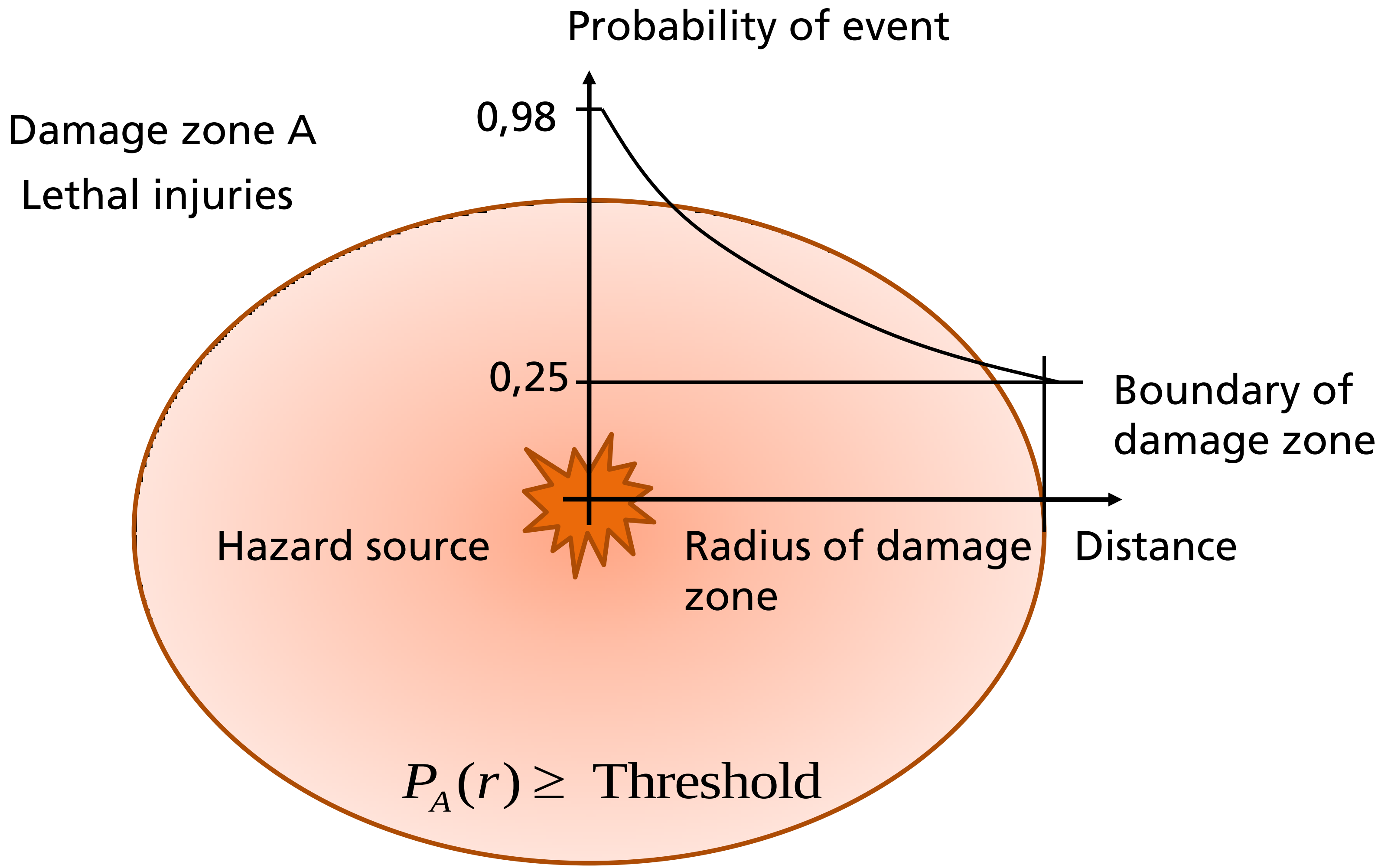
In front of barricade



EOD Damage Assessment – Damage Zone

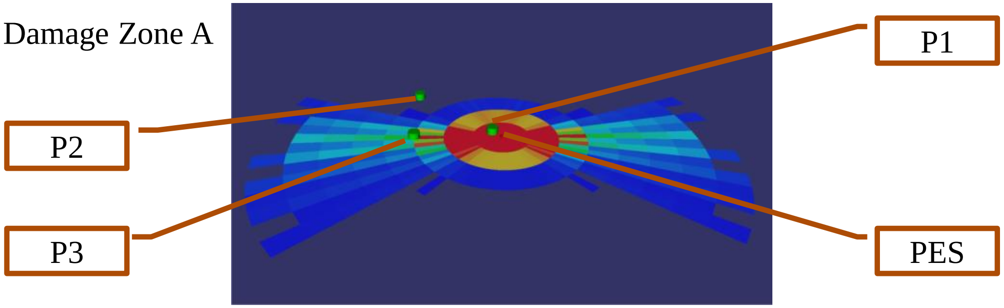
DZ	Effect On			
	Persons	Buildings / Infrastructure	Vehicles	Aircraft
A	Lethal injuries	Complete destruction of buildings, ammunition and material	Complete destruction	Complete destruction
B	Serious injuries	Serious damage of buildings	Damaged but still usable	Heavily damaged, not ready-to-fly
C	Slight or no injuries	Slight or no damage of buildings	Slight or no damage	Slight or no damage, ready-to-fly

EOD Damage Assessment – Damage Zone

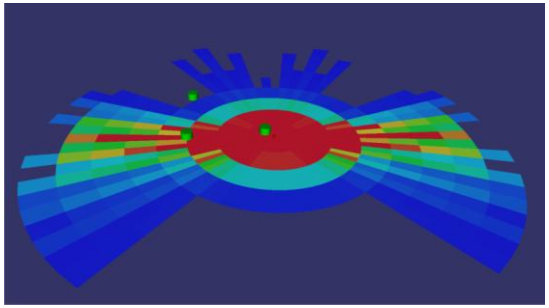


EOD Damage Assessment – Damage Zone

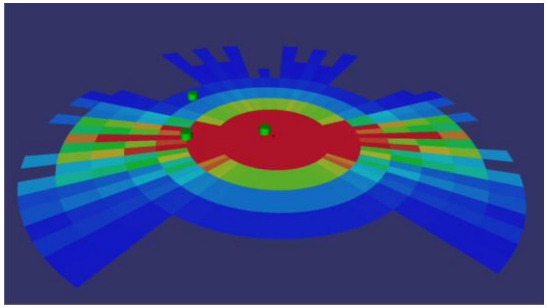
(a) Damage Zone A



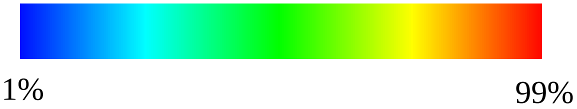
(b) Damage Zone B



(c) Damage Zone C



Probability of Event



Conclusions

- Completely new implementation of the software using state-of-the-art techniques
- Three dimensional scenario representation
- New hazard sources
- Treatment of barricades and fragment shadows
- Arbitrary position and orientation of a hazard source
- EOD specific damage zones